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Reclamation of an Oil Sands Tailings Storage Facility: Vegetation and Soil Interactions

by

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ABSTRACT

The Southwest Sand Storage Facility (SWSS) is a 25 km^2 oil sands tailings storage structure, located at Syncrude Canada Ltd., within Alberta's Athabasca Oil Sands Region. Reclamation challenges arise from the interactions of soil chemical, physical and hydrologic parameters that may be limiting revegetation success. This study examined these interactions so that appropriate reclamation and revegetation measures can be made and final reclamation success can be achieved.

The plant communities on Cells 32 and 46 were primarily composed of early successional, ruderal species. Salinity and soil moisture were not affecting revegetation success on Cell 32 but sodicity and soil nutrient deficiencies were. On Cell 46, salinity, although higher than on Cell 32, was not currently affecting revegetation success; but sodicity, soil nutrient deficiencies and low reclamation soil depths were.

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CHAPTER I. INTRODUCTION

1.0 BACKGROUND

1.1 Oil Sands Mining

The Athabasca oil sands in the boreal forest region of Northern Alberta, Canada represent one of the single largest deposits of oil in the world with an estimated bitumen volume of 1.7 trillion barrels (Fung and Macyk 2000). Within the Athabasca oil sands there are currently three commercial surface mining plants Syncrude Canada Ltd. (Syncrude), Suncor Energy Inc. and Albian Sands Energy Inc. The largest of the commercial plants is Syncrude, which will produce 350,000 barrels of oil per day by 2005 (Syncrude 2004).

The Athabasca oil sands can be recovered through surface mining techniques due to the close proximity of the ore layer to the surface. The first step in the mining process is the removal of the overburden layer, which varies in depth to a maximum of 45 m, after which it is not economical to mine oil sands through surface mining techniques. The overburden is stockpiled adjacent to the mining pit or within the pit in areas already mined. The next step is mining of the oil sands ore using a shovel and transport with heavy haulers to a central collection point on the mine. The ore is mixed with water and transported to the plant in a slurry via a network of pipes and pumps or the ore is transported via a conveyer belt and stockpiled outside the extraction plant. The raw ore then enters the extraction process where hot water and caustic are mixed with the ore via the Clark hot water extraction process pioneered by Dr. Karl Clark. The slurry is fed into a vessel where it separates into sand, water and bitumen layers. The bitumen is skimmed off the top, cleaned and processed further. The sand and water portion form the tailings material with additions of clay particles, silt and a minor fraction of residual hydrocarbons. The clay particles and silt are from overburden material admixed with the ore during mining and the residual hydrocarbons result from the extraction process, which is approximately 96% efficient.

Through the mining process, large amounts of coarse tailings sand are produced. Syncrude currently transports the tailings within a water slurry and deposits them on the Southwest Sand Storage facility (SWSS), located on their lease site. The SWSS became

operational in 1991 and it is currently one of the largest tailings sand storage facilities in the world, covering an area of 25 km^2 (AGRA 1997). Fung and Macyk (2000) outlined eight major limitations for the reclamation of tailings sand including high erosion potential, low water storage capacity, high soluble sodium content, poor nutrient status, hydrophobic qualities, absence of organic matter, low cation exchange capacity and absence of microbial activity. Thus, an immense environmental challenge exists in the reclamation and revegetation of the SWSS.

1.2 Tailings Sand Revegetation

Development of the oil sands industry has disturbed approximately 40,000 ha of land through the mining process and disposal of wastes (Fung and Macyk 2000). As an aspect of their operating approval agreements, oil sands companies are responsible for reclaiming this disturbed land to equivalent, predisturbance land capability (Alberta Environment 1993). The end land use goal of the SWSS is productive forestry. To achieve this, reclamation is initiated with the placement and redistribution of tailings sand. Reclamation soil and fertilizer are then applied. Revegetation is dependent on the desired target ecosite, based on the soil capability classification and moisture regime of the area (OSVRC 1998). Once the target ecosite is identified, supplemental plantings of tree and shrub species prescribed for the area are made. On the SWSS, concerns with soil chemical and physical properties and soil moisture have delayed further revegetation activities. Thus it is necessary to understand the interactions of these parameters and the effects they may have on the overall reclamation and revegetation success of the SWSS before successful reclamation strategies can be developed.

2.0 Literature Review

2.1 Tailings Sand Revegetation

The majority of revegetation research conducted on oil sands tailings has focused on woody species, specifically jack pine (*Pinus banksiana* Lamb.), black spruce (*Picea mariana* (Mill.) BSP.), white spruce (*Picea glauca* (Moench) Voss) and trembling aspen (*Populus tremuloides* Michx.) and the effects of the chemical properties of tailings sand

on their growth and survival. This research has generally been conducted in growth chambers or laboratories in controlled environments

Croser et al. (2001) studied the effects of different concentrations of two salts present in oils sands tailings, sodium sulphate and sodium chloride, on germination, emergence and early growth of jack pine, black spruce and white spruce. They concluded that vegetation response to these salts is highly dependent on species and salt concentrations and suggested that white spruce and jack pine were the most and least significantly affected by salt treatments, respectively.

Apostal et al. (2002) investigated the combined effects of boron, sodium chloride and sodium sulphate on growth, injury and ion composition of jack pine seedlings. Seedlings treated with only boron had reduced new growth; with the combination of boron, sodium chloride and sodium sulphate, seedlings exhibited significantly higher growth reduction and salt injury. Chloride appeared to be the major factor contributing to seedling injury.

Khasa et al. (2002) researched inter- and intra-specific variability of selected boreal woody species to various salt concentrations to determine their potential suitability for reclamation of saline habitats. They concluded that within genotypes of each species significant variations were exhibited as a response to the different salt treatments. Overall the best performing seed lots were trembling aspen and jack pine (origin for both Fort McMurray, Alberta).

Redfield and Zwiazek (2002) conducted a study to determine the importance of drought tolerance characteristics in black spruce seedlings in tolerance of sodium chloride and sodium sulphate. Water potential and stomatal conductance of black spruce decreased as a direct result of sodium chloride and sodium sulphate treatments, indicating that both salts induced water deficit stress. They also concluded that sodium chloride produced more visible needle injury and greater shoot electrolyte leakage than sodium sulphate, suggesting that chloride played a greater role in needle injury than sulphate.

2.2 Composite Tailings

Composite tailings (CT) are produced through the addition of gypsum to mature fine tailings to produce a non-segregated deposit (Renault et al. 1998). Although this

research did not focus on CT, revegetation research focused on CT may provide useful information. The high addition of gypsum required to solidify the mature fine tailings results in significant addition of sulphate from the gypsum and sodium and calcium from exchange sites on clays. The majority of revegetation research conducted on CT has also focused on woody species.

Renault et al. (1998) investigated the impact of gypsum treated CT water on the viability of northern boreal species to determine relative salt tolerance and suitability of these selected plant species for revegetation. They concluded that wild red raspberry (*Rubus idaeus* L.) and wild strawberry (*Fragaria virginiana* Duchesne) seedlings were most susceptible to damage, while seedlings of white spruce, black spruce and lodgepole pine (*Pinus contorta* Louden) survived but showed some effects. There were also rapid losses of leaves in peachleaf willow (*Salix amygdaloides* Anderss.) and trembling aspen seedlings, which were quickly replaced by new, morphologically different leaves. Northwest poplar (*Populus deltoides* Marsh. x *Populus balsamifera* Bartr. cv.) and red osier dogwood (*Cornus stolonifera* Michx.) showed high tolerance to all treatments. High individual species variability within conifer seedlings suggested genetic differences in conifers should be considered in the selection of genotypes for revegetation.

Renault et al. (2001) studied the effects of composited tailings water on growth parameters, photosynthetic rates, chlorophyll content, water relations and ion accumulation in red osier dogwood seedlings. Exposure of red osier dogwood seedlings to high salinity composited tailings water changed ionic content in plant tissues including large accumulations of sodium and chloride in roots, stems and leaves, reducing shoot growth. They concluded that the tolerance of seedlings to composited tailings water included restriction of sodium transport from roots to shoots. They noted that the high pH of composited tailings water is of concern and may be partly responsible for leaf chlorosis and growth reductions.

Franklin et al. (2001) examined the effects of CT sand treated with sodium chloride and sodium sulphate on the growth and elemental composition of jack pine. They hypothesized that nutrient imbalances, in addition to tissue salt levels, may explain both growth reductions and toxicity symptoms attributed to direct ion toxicity of sodium and chloride. They concluded that observed necrosis was more severe in chloride treated

plants as the amount of sodium in the treatment solutions increased. This suggested that chloride impeded the ability of plants to restrict movement of sodium and other cations, thus injury and growth reductions resulted from the accumulation of mineral nutrients in the plant tissues. Injury to seedlings did not appear to be due to nutrient deficiencies.

Franklin et al. (2002) studied tolerance of jack pine to exposure of raw CT water to test the hypothesis that injury and growth reduction in seedlings were related to increased shoot tissue concentrations of salt ions or nutrient deficiencies. They concluded that the greatest injury to jack pine was caused by ion toxicity, specifically sodium and chloride. Nutrient deficiency was not directly related to reduced plant growth or injury, but the nutrient status of plants appeared to be related to both high pH and salinity rates. They suggested that seedlings exhibited losses of chlorophyll A, which could cause long-term reductions in growth.

2.3 Other Revegetation Studies Associated with Tailings Sand

The majority of research conducted on the revegetation of tailings sand has been industry, government or consulting reports focusing on establishment and survivorship of woody species.

Dai and Salayka (1983) assessed different seeding methods of a grass legume seed mix and survivorship of woody species planted within different seeding treatments. Seeding rate for broadcasting and drill seeding could be below 11 and 6 kg/ha, respectively, to produce sufficient ground cover to prevent surface erosion. They concluded that survival of woody seedling species was generally very low due to moisture stress caused by heavy competition from seeded grasses and legumes.

Other studies focused on the most appropriate time of year for planting woody species. Berg and Dai (1986) concluded there was no difference in fall or spring planting for jack pine and little or no competition from grass and legume species improved both spring and fall plantings of woody species. Konowalyk and Fung (1985) concluded there was no definite trend to indicate the best time of outplanting woody species but there were certain times to avoid planting. These times included early spring (May) and late fall (October) due to increased frost risk and mid-summer (July) when hot and dry conditions occur and grass/legume competition is at peak.

Other studies concentrated on the feasibility of certain woody species for revegetation of tailings sand. Blackmore (1982) focused on caragana (*Caragana arborescens* Lam.) and concluded that it should always be mixed with other tree and shrub species and never exceed 25% of the total species planted in the first year. In subsequent years it should never be allowed to exceed 50% of the total species planted. Fung (1992) studied the feasibility of directly planting poplar stems and concluded that root initiation and subsequent growth of poplar stem cuttings depended on a continuous supply of soil moisture and high relative humidity surrounding the cuttings. This method may not be effective because these moisture conditions are not common in a field situation.

Macyk and Faught (2001) assessed the impact of tailings water on vegetation cover of the SWSS, north of this study site. They concluded that the overall quality of seepage water consistently deteriorated for the 4 years of the study with increases in electrical conductivities, sodium and sodium adsorption ratio. They suggested water from tailings was impacting soil reclamation. Watering native vegetation control plots and vegetation on the SWSS with tailings water, yielded major differences in elemental content of plant tissues for sodium, boron and manganese. They concluded that the tailings sand was much drier at upper slope positions than at mid and lower slope positions and moisture levels in reclamation soil increased from upper slope to mid slope to lower slope positions.

3.0 Research Objectives

The overall objective of this study is to characterize the interactions of specific soil chemical, physical and hydrologic characteristics on the plant community established on the SWSS. The results of this study may then be used to contribute to the development of appropriate reclamation strategies for tailings sand storage facilities, leading to successful reclamation and the attainment of end land use goals.

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CHAPTER II. VEGETATION AND SOIL CHEMICAL AND PHYSICAL INTERACTIONS ON A TAILINGS SAND STORAGE FACILITY

1.0 INTRODUCTION

The Athabasca oil sands in the boreal forest region of Northern Alberta, Canada represent one of the single largest deposits of oil in the world with an estimated bitumen volume of 1.7 trillion barrels (Fung and Macyk 2000). Development of the oil sands industry has disturbed approximately 40,000 ha of land through the mining process and disposal of wastes (Fung and Macyk 2000). The oil sands companies are responsible for reclaiming this disturbed land to equivalent, predisturbance land capability (Alberta Environment 1993).

Challenges associated with the reclamation of tailings sand structures include the massive overall size (25 km^2) and the lack of internal drains, which might allow seepage water into the reclaimed soil (Syncrude 2004). In addition, elevated ionic concentrations of the tailings material, specifically sodium, chloride and sulphate, increase the risk for soil salinity and sodicity problems. A saline soil has an electrical conductivity >4 dS/m, an exchangeable sodium percentage of <15 and pH usually <8.5 (Powter 2002, Chhabra 1996) or contains soluble salts, in such quantities that they interfere with the growth of most plants (Powter 2002). Munns (1993) suggests that plant response to salinity is one the most widely researched subjects in plant physiology. The problems associated with plant growth in saline soils are mostly related to water deficiencies and ion toxicity (Greenway and Munns 1980). The increasing salt content in soils has negative effects on plant water balance by increasing the osmotic difference between plant roots and the soil water. In saline soils the osmotic potential (which results from the materials dissolved in the soil water) is stronger (more negative) than the gravitational and capillary potentials, effectively not allowing water to diffuse into plant roots (Troeh and Thompson 1993). Ion toxicity is a problem as salt ions can accumulate in plant tissue in qualities that are detrimental to plant health.

The sodium adsorption ratio (SAR) is a useful index of the sodicity or relative sodium status of soil solutions. Soils with SAR >13 are usually considered sodic (Janzen 1993). Other researchers define sodic soils as having an SAR of $\geq$ 15 (Howat 2000), more than 15% of their cation-exchange sites occupied by sodium ions (Troeh and

Thompson 1993) or a soil containing sufficient exchangeable sodium to interfere with the growth of most plants (Powter 2002). The result of sodic soils is a soil physical problem, as the high concentration of sodium displaces smaller radius ions on the soil cation exchange sites and causes soil dispersion. This dispersion creates the negative effects on plants and causes the soil to have low permeability to water, air and roots (Troeh and Thompson 1993). As SAR increases above 12, the dispersion of the soil increases distinctly (Leskiw 1998). The high concentration of sodium ions also can result in a high pH because of the basic influence of the sodium ions (Troeh and Thompson 1993).

The inherent low nutrient status of the tailings sand and reclamation soil which typically consists of a peat mineral mix also poses a reclamation challenge. The tailings material is sand and thus does not contain nutrients and peat is typically deficient for micronutrients and known to have low quantities of plant available macronutrients (Land Resource Network Ltd. 1993).

Soil physical properties such as reclamation soil depth and texture also present reclamation challenges. The reclamation soil acts as a tailings stabilizer and serves as an appropriate growth medium for vegetation (Barth 1986). The reclamation soil must be deep enough to allow for deeper rooting species and serve to protect these roots, from the underlying tailings material. The reclamation soil can also act as a capillary barrier or a capillary zone to protect the rooting zone from the negative chemical properties of the underlying tailings (Barth 1986). If reclamation soil depth is not adequate then its beneficial aspect may be lost. Soil texture has many implications for plant growth including the soils ability to store water, provide nutrients and be permeable to air, water and roots (Troeh and Thompson 1993).

Previous research on tailings sand structures focused on soil physical properties (Yarmuch 2003), soil moisture (Moskal 1999, Chaikowsky 2003) and hydrogeology of the SWSS (Price 2004). Most vegetation studies focused on a few tree species (Redfield 2001, Franklin 2002, Apostol 2003) or were conducted in controlled laboratory settings (Renault et al. 1999, Renault et al. 2000, Croser et al. 2001).

The dynamic interactions of vegetation and the reclaimed tailings sand environment have not been studied on a field scale. To address that gap, this study examined the soil properties of salinity, sodicity, nutrients and reclamation topsoil depth

and texture and their influence on plant community development on the SWSS, providing a comprehensive link between soil and revegetation. As oil sands mining continues, the knowledge base for successful reclamation methods must be expanded so that the structure and function of the disturbed ecosystem can be restored and a desired end land use obtained.

2.0 OBJECTIVES

The objective of this study was to characterize the interactions of specific soil chemical and physical properties on plant community development. Research questions of specific interest include the following.

- Are salinity and sodicity inhibiting plant community development?
- Are insufficient soil nutrients inhibiting plant community development?
- Are soil physical parameters inhibiting plant community development?

3.0 MATERIALS AND METHODS

3.1 Study Area

The study area is located in the Athabasca oil sands deposit, approximately 50 km north of Fort McMurray, Alberta at Syncrude's Mildred Lake facility (Figure 2.1). The study area has short, cool summers with long, cold winters. Mean annual temperature is 0.7 °C with January being the coldest month (-18.8 °C) and July the warmest (16.8 °C) (Environment Canada 2003). Mean annual precipitation is 455.5 mm, with 342.2 mm occurring as rain and 155.8 cm occurring as snow (Table 2.1).

Within the Athabasca oil sands the ore bearing materials originate from the Cretaceous Period McMurray Formation, developed through deposition of organic material within fluvial and tidal conditions (Wedage et al. 1998). The overall thickness of the McMurray Formation varies depending on underlying unconformity but its maximum thickness is over 150 m (Flach 1984). The McMurray Formation is underlain by shales and limestones of the Waterways Formation (Devonian) and overlain by marine shale and sandstone of the Clearwater Formation (Conly et al. 2002). Above the Clearwater Formation, marine sandstone from the Grand Rapids Formation dominates (Flach 1984).

The characteristic mineral soils in the upper slope positions are Orthic Gray Luvisols with transitions to Gleyed Gray Luvisols in mid to lower slope positions (Turchenek and Lindsay 1982). In low or toe slope positions Gleysolic soils dominate and Organic soils are present within depressions. Fibrisols and Mesisols are the most commonly occurring great groups in the study area (Turchenek and Lindsay 1982).

The natural vegetation of the area is typical of the Boreal Mixedwood Ecological area (Alberta Environmental Protection 1994). The upland areas are primarily composed of deciduous forests with the dominant tree species being trembling aspen (*Populus tremuloides* Michx.) and balsam poplar (*Populus balsamifera* L.). On drier, sandier sites communities of jack pine (*Pinus banksiana* Lamb.) dominate. Within lowlands the dominant tree species are black spruce (*Picea mariana* (Mill.) BSP), white birch (*Betula papyrifera* Marsh.) and tamarack (*Larix laricina* (Du Roi) K. Koch). The climax tree species are white spruce (*Picea glauca* (Moench) Voss) and balsam fir (*Abies balsamea* (L.) P. Mill) but they rarely attain their climax structure due to the short return cycle of fire and the ability of trembling aspen to dominate post-fire areas (Stinger 1976). Beckingham and Archibald (1996) stated that the understory vegetation consists of a variety of shrubs and forbs including beaked hazelnut (*Corylus cornutat* Marsh), prickly rose (*Rosa acicularis* Lindl.), low-bush cranberry (*Viburnum edule* (Michz) Raf.), saskatoon (*Amelanchier alnifolia* (Nutt.) *ex* M. Roemer), Canada buffalo-berry (*Shepherdia canadensis* (L.) Nutt.), twin-flower (*Linnaea borealis* L.), green alder (*Alnus crispa* (Ait.) Pursh), bunchberry (*Cornus canadensis* L.), wild sarsaparilla (*Aralia nudicaulis* L.) and dewberry (*Rubus pubescens* Raf.).

3.2 Study Site

3.2.1 South West Sand Storage Facility

The SWSS is a 25 km^2 hydraulically filled tailings sand storage facility, located in the southwest corner of Syncrude's Lease 17 (Figure 2.2). Tailings are produced through the bitumen extraction process; they are the remaining ore body after the bitumen has been removed and thus contain a large fraction of sand. The sand is 96 to 99% SiO_2, 0.5 to 0.9% Al_2O_3 and 0.1 to 0.9% Fe (Mikula et al. 1996). With this coarse sand, water, clay particles, silt and a minor fraction of residual hydrocarbons form the tailings material.

Water is introduced through the Clark hot-water extraction process and becomes high in chlorides, sulphates and sodium. Clay particles and silt are from overburden material admixed with the ore during mining. Residual hydrocarbons result from the extraction process which is approximately 96% efficient. The SWSS receives the tailings sand, transported in slurry form, from the extraction plant via a network of pipes and pumps. This slurry is allowed to settle and dewater until it is practical for machinery to redistribute the sand material.

The SWSS became operational in 1991 with the establishment of a perimeter dyke, which was then followed by an ongoing process of cell construction (AGRA 1997). It currently holds an estimated 500 million m^3 of tailings sand and upon closure will hold over 800 million m^3 (Syncrude 2004). The construction of cells includes the formation of terraced slopes with backslopes (or benches) from the toe ditch to the beach. Spillways (or swales) collect surface water and transport it from the structure to the toe ditch. The SWSS was designed to have an external overall slope of 20H:1V to ensure stability of the structure (AGRA 1997). Once the tailings material is placed, reclamation is initiated on the slopes with placement of reclamation soils, fertilizer application and revegetation. The SWSS presents distinctive reclamation challenges in its massive size. Its construction without internal drains may result in tailings water seeping from the dyke into the reclamation soils, which could affect reclamation success.

3.2.2 Cell 32

Cell 32, a 2.5 km^2 area on the east side of the SWSS (Figure 2.3), currently consists of 4 slopes, 3 backslopes, a flat area at the toe and a beach at the top (Figure 2.4). Slopes are approximately 90 m in length and graded to 10%. Backslopes are approximately 80 m in length and graded to 2%. This study utilized the flat toe area, the first two bottom slopes and the first two backslopes (Figure 2.4). On the backslopes, constructed waterways collect runoff and seepage water and are designed to transfer it laterally to the swale that forms the southern boundary of the site. The water is then transferred down the swale to the toe ditch that collects water from the base of the SWSS.

The cell is undergoing progressive reclamation which started in 1995 with the placement of reclamation soil material. The reclamation soil material was designed to

have an 80 cm depth and consisted of a peat secondary mix. This material was salvaged from pre-mined areas and is a mixture of peat and mineral materials resulting in a mineral soil (<17% organic carbon dry weight basis). It was obtained by either overstripping peat into the mineral soil, or by placing peat material and then rotovating into underlying mineral material (Yarmuch 2003).

After the reclamation soil placement the area was fertilized with a 10-30-15-4 mix, applied at a rate of 364 kg/ha. Reforestation occurred in fall 1996 with the planting of trembling aspen, white spruce, jack pine, red-osier dogwood (*Cornus stolonifera* Michx.), hybrid poplar (species unknown) and Siberian larch (*Larix sibirica* Ledeb.) at an average stem density of 2,000 stems/ha. Jack pine was planted only along the crest lines on the slopes and backslopes (Anderson 2003).

3.2.3 Cell 46

Cell 46 is a 1.5 km^2 area located on the west side of the SWSS (Figure 2.3) consisting of one forward facing slope and one continuous slope. This study utilized the one forward facing slope and divided it into a lower and upper slope (Figure 2.5). The cell is undergoing progressive reclamation which started in 2000 with the placement of reclamation soil material on the forward slope. The reclamation soil material was designed to have a 35 cm depth and consisted of 20 cm of secondary material capped with 15 cm of a peat/mineral mix. The soil material was harvested from pre-mined areas. The secondary material consisted of suitable quality upland soil or surficial geological material harvested to a depth where the material is considered of poor quality for plant growth (Yarmuch 2003). The peat/mineral mix is harvesting by overstripping peat soil so some mineral soil is included with the peat. The remaining area of the cell (continuous slope) was capped with the same reclamation soil in 2002. Cell 46 has not received any further reclamation measures.

3.3 Vegetation

For this study, Cells 32 and 46 were divided horizontally along each slope and back slope, and then further divided into 5 equal distance vertical blocks (1, 2, 3, 4 and 5). Within each block three vegetation plots were denoted: low cover (<20% canopy

cover), medium cover (20 to 60% canopy cover) and high vegetation (> 60% canopy cover). Individual plots were at least 2 m^2 in size and represented one of the three canopy cover categories.

Vegetation parameters were assessed through stratified random sampling using 0.1 m^2 (0.2 x 0.5 m) quadrats. Prior to sampling, a species area curve determined that three quadrats per vegetation plot were necessary to capture at least 80% of the plant species. Within each plot, a quadrat was assessed in the geographic center and the remaining two quadrats were randomly located in a grid of 12 quadrats (Figure 2.6).

In each quadrat, plant species composition and distribution were assessed through total canopy cover, canopy cover by species and ground cover (% bare ground, % litter, % live vegetation and % rocks). Total canopy cover was measured by looking down on the canopy and not moving any of the vegetation to determine overlap. Individual species canopy cover was measured as the total canopy cover of each species within the quadrat. Ground cover was determined by a visual assessment of each parameter at the ground surface. Vegetation health was assessed at each quadrat using a visual scale of 1 though 3, with 1 being healthy, 2 showing some signs of stress and 3 in very poor health (Table 2.2). Vegetation measurements were made in the middle of the growing season (July 2003) to ensure the assessment captured the full extent of foliage.

3.4 Soils

Soil was sampled in August 2003 at the geographic center of each vegetation plot, corresponding to the location of the first quadrat of the vegetation assessment. Sampling was conducted with a 5.08 cm Dutch auger at 0 to 10 cm, 10 to 20 cm and then at 20 cm depth intervals until the tailings sand was reached, after which one additional 20 cm depth sample was obtained from the tailings sand. Three adjacent holes were needed to obtain the required volume of sample for the 0 to 10 cm and 10 to 20 cm depth intervals. These adjacent holes were placed within the area of vegetation assessment and the central hole was used for the remaining depth intervals. All samples were composited from their depth intervals, placed in a cooler within 1 hour and kept cool until laboratory analyses.

Laboratory soil analyses were conducted at EnviroTest Laboratories, Edmonton, and included % saturation, pH, electrical conductivity, sodium adsorption ratio, cations

(calcium, potassium, magnesium and sodium) and anions (chloride, nitrate, nitrite, sulphate and phosphate) from a saturated paste extract (Janzen 1993). On the 0 to 10 cm and 10 to 20 cm depth samples additional analyses included the DTPA extractable micronutrients of copper, iron, manganese and zinc (Liang and Karamanos 1993) and organic matter and organic carbon by the wet oxidation-redox titration method (Tiessen and Moir 1993). For 13 samples on Cell 46, where organic matter content was > 20%, organic matter content was determined by the loss on ignition method at 375 °C (McKeague 1978). The 0 to 10 cm interval was analyzed for particle size (% sand, % silt and % clay) by the hydrometer method at the University of Alberta, Natural Resources Analytical Lab (Sheldric and Wang 1993). Samples were treated with hydrogen peroxide to remove organic matter. Depth to the tailings sand was measured during soil sampling to denote the depth of reclamation soil.

3.5 Meteorological Parameters

Meteorological data for 2003, 2004 and the long term climate normal from 1971 to 2000 were obtained from the Environment Canada monitoring station located at the Fort McMurray Airport (56° 39' N and 111° 13' W). In addition a meteorological station was installed on the upper back slope of Cell 32 and the upper forward slope of Cell 46 by O'Kane Consultants Inc. Air temperature, solar radiation, precipitation, relative humidity, wind speed and wind direction were recorded hourly. Although the stations on Cell 32 and 46 did record snow fall, due to a large discrepancy in the data from the cells and the Environment Canada station, caution is suggested in the interpretation of the total precipitation data from Cells 32 and 46.

3.6 Statistical Analyses

3.6.1 One way ANOVA with blocking

A one way ANOVA with blocking was performed with SYSTAT statistical software. Vegetation data for Cell 32 were divided into three cover classes (or treatments) of low, medium and high. For Cell 46 only two cover classes (or treatments), low and medium, were selected as none of the vegetation plots had >60% cover for the high vegetation treatment. Normality was assessed through visual inspections of the data on

histograms and by analyzing kurtosis and skewness of the data. The data were not normal and therefore were transformed before statistical analyses. A log or a log +1 transformation was applied to the non-normal data. A one-way ANOVA with blocking was used for statistical analysis with slope as the blocking factor since it was not a replicate and to ensure variations between slopes were not confused for variations within treatments. For Cell 32 a Tukeys post hoc test for significant differences between treatments was performed (Zar 1999). In all statistical analyses, a confidence level of 95% was chosen ($\alpha = 0.05$) to distinguish statistically significant variation.

3.6.2 Species richness and indicator species analyses

For Cell 32, statistical comparisons among the three vegetation treatments for species richness were performed using the non-parametric analysis of variance Kruskal-Wallis test (Zar 1999) with SYSTAT statistical software. A non-parametric method was selected due to the low sample size and non normality of the data. To effectively determine if the vegetation treatments were different it was necessary to have equal sample sizes. Therefore 6 and 4 randomly selected plots from the low and medium vegetation treatments, respectively were removed. To determine which treatments were significantly different, a Nemenyi post hoc test was used (Nemenyi 1963 in Zar 1999). For Cell 46, statistical comparisons between the two vegetation treatments for species richness were performed using the non-parametric analysis of variance Mann-Whitney test with SYSTAT statistical software. The Mann-Whitney test is identical to the Kruskal-Wallis test, but is desirable when two treatments are compared (Zar 1999). Equal sample sizes were required so 10 randomly selected plots from the low vegetation treatments were removed. In all statistical analyses, a confidence level of 95% was chosen ($\alpha = 0.05$) to distinguish statistically significant variation.

To determine which individual species were prominent within each vegetation treatment, the indicator species analysis approach of Dufrene and Legendre (1997) with PC-ORD software (McCune and Mefford 1999) was performed. For each cell, indicator values corresponding to the combined frequency and relative abundance of each species were obtained for each vegetation treatment (Boudreault et al. 2002). The maximum

indicator value was then tested by using a Monte Carlo permutation test with 1,000 iterations to determine whether it was significantly different from other values.

3.6.3 Ordination

A nonmetric multidimensional scaling ordination (NMS) was performed with PC-ORD software (McCune and Mefford 1999) to relate plant community structure to the underlying soil chemical and physical gradients. NMS is a non-parametric ordination technique that performs well with data sets where the underlying species response patterns cannot be specified a priori and thus fits the objectives of this study (Clarke 1993). NMS ordination was performed on the vegetation data and then soil chemical and physical parameters were related through a joint plot. The joint plot method shows the relationship between a set of variables (usually environmental, soils in this study) and ordination scores (vegetation in this study) (McCune and Mefford 1999). The diagrams, produced from joint plots, indicate plots and species ordination scores with radiating vector lines of environmental attributes. The angle and length of these vector lines distinguish the direction and strength of the relationship.

For Cell 32 one plot (Low, Bench 4, Replication 2) and two soil variables (nitrate + nitrite and phosphorous) were identified as outliers (more than 2 standard deviations away from the mean) through outlier analysis using Sorensen distance measures. This one plot and the two soils variables were removed prior to analyses as outliers can profoundly influence multivariate analysis (McCune and Mefford 1999). For Cell 46 nitrate + nitrite and phosphorous were identified as outliers and removed. Due to many missing values for organic carbon, this variable was also removed for Cell 46. For both cells total canopy cover was removed prior to analyses as it was the sum of all species already included in the ordination and thus might have falsely strengthened the ordination. Before analyses only species present in at least two plots were incorporated into the ordination, resulting in the removal of 11 species for Cell 32 and 9 species for 0 to 10 cm depth interval and 10 species for the 10 to 20 cm depth interval in Cell 46.

Prior to running the ordination for Cells 32 and 46, vegetation data were transformed with a square root transformation to improve normality. For each cell the vegetation NMS ordinations were joint plotted with soil variables from the 0 to 10 and 10

to 20 cm depth increments. For Cell 32 the total number of sites included in the ordination was 65 from the original of 70 due to the loss of soil samples for 4 plots and the deletion of 1 plot due to outlier constraints. For Cell 46 all 25 plots in the original design were used for the 0 to 10 cm depth, 23 plots were used in the 10 to 20 cm depth increment as a result of low reclamation soil depths and exclusion of 2 plots where the 10 to 20 cm depth was tailings sand not reclamation soil.

4.0 RESULTS AND DISCUSSION

4.1 Meteorological Parameters

In 2003 mean temperature was similar to the long term climate normal (LTN) (Environment Canada 2004) (Tables 2.1, 2.3, 2.4 and 2.5). Mean temperatures in 2003 at the airport were higher in January, July, August and December but lower in February and March compared to the LTN, for the remaining months mean temperatures were similar. Total precipitation in 2003 (375.1 mm) was slightly above the LTN (342.2 mm) but more precipitation fell during the months of May and June and less fell during July and August. In September total precipitation was substantially greater (89.4 mm) compared to the LTN (46.8 mm). Temperature and precipitation from Cells 32 and 46 showed a similar trend to that at the airport.

In 2004 the mean temperature for the airport and Cells 32 and 46 were similar to the LTN. The mean temperature in 2004 was higher in February and July but lower in January, May and from August to October than the LTN. Total precipitation in 2004 was less from January to July (200.3 mm) compared to the LTN (265.1 mm).

4.2 Vegetation

4.2.1 Canopy cover and plant health

Average total canopy cover within Cell 32 was 37.8%. The three vegetation treatments, low (9%), medium (37%) and high (77%), were all significantly different (Table 2.6). Within benches, highest total canopy cover occurred on the lower forward slope (45%) and lowest cover occurred on the toe slope (20%) (Table 2.7).

For Cell 46 average total canopy cover was 19%. The low (8%) and medium (35%) vegetation treatments were significantly different (Table 2.6). Within benches, highest total canopy cover occurred on the lower forward slope (22%) and lowest total canopy cover occurred on the upper forward slope (14%) (Table 2.7). Highest total canopy cover was expected on the lower forward slopes on Cells 32 and 46 since these slopes were the oldest on each cell, allowing more time for vegetation growth and plant community development.

For Cell 32, only 5 individual quadrats, all from low vegetation treatments, received a plant health rating of 2 indicating some signs of stress. For Cell 46 only 1 quadrat, from the low vegetation treatment, received a plant health rating of 2. No quadrats received a rating of 3 for very poor health.

4.2.2 Ground cover

For Cell 32 average bare ground was 38%. The low vegetation treatment (88%) was significantly different from medium (9%) and high (7%) treatments (Table 2.6). Within benches highest bare ground occurred on the toe slope (73%) and lowest on the upper forward slope (25%) (Table 2.7). These two benches were significantly different from each other. The low vegetation treatment had significantly more rocks and significantly lower litter, live vegetation and moss than medium and high treatments.

Average bare ground for Cell 46 was 55%. The low (88%) vegetation treatment was significantly different than the medium (9%) (Table 2.6). Litter, live vegetation and moss for the low vegetation treatment were all significantly lower than for the medium.

4.3 Soil Texture

For Cell 32, average soil texture for the 0 to 10 cm depth interval was sandy clay loam for the low vegetation treatment and clay loam for the medium and high treatments (Table 2.8). Clay, silt and sand did not differ significantly among vegetation treatments.

For Cell 46, soil texture for the 0 to 10 cm depth interval was clay loam for the low and loam for the medium treatment. Clay, silt and sand did not differ significantly among vegetation treatments.

4.4 Reclamation Soil Depth

For Cell 32, average soil depth was 80.2 cm. Topsoil depth ranged from 45 to 100 cm for the low, 40 to 120 cm for the medium and 40 to 100 cm for the high treatment. The three vegetation treatments, low (78 cm), medium (81 cm) and high (81 cm) were not significantly different (Table 2.9).

For Cell 46, average soil depth was 35.6 cm. Topsoil depth ranged from 10 to 60 cm for the low and from 28 to 65 cm for the medium treatment. Depth of the low vegetation treatment (32 cm) was significantly different from that of the medium (41 cm) (Table 2.10).

The results for Cells 32 and 46 were expected. The average topsoil depth was consistent with the prescribed reclamation procedure of an 80 cm depth on Cell 32 and 35 cm for Cell 46. Although the average is consistent with the reclamation practices of each cell, the large range of topsoil depths should be noted. Low topsoil depths on Cell 46 may be affecting plant community development as the low vegetation treatment had significantly lower soil depths. Similar conclusions were made by Fisher et al. (2000) who examined soil amendment depth over fluvial mine tailings and found increasing soil amendment depth significantly enhanced vegetation production of willow cuttings. Gildon and Rimmer (1993) also found increasing soil cover thickness over colliery spoil increased grass yield, particularly on a site with potentially acidic spoil materials.

Low reclamation soil depths on Cell 46 could negatively affect plant community development because of the rooting characteristics of boreal forest vegetation. Stong and Roi (1983) in a study of root density and depth patterns of four boreal forest age sequences in Alberta found 50% of all roots located within 15 cm of the surface. This is supported by Canadell et al. (1996) who suggested that boreal forest vegetation has a maximum rooting depth of 2.0 ±0.3 m.

4.5 Soil pH

For Cell 32, soil pH for the 0 to 10 cm depth interval ranged from 4.8 to 8.8. The low vegetation treatment (7.5) was significantly different from the medium (7.1) and high (7.2) treatments (Table 2.9). This also occurred for the 40 to 60 cm depth interval, where the low vegetation treatment (7.9) was significantly different from the medium (7.4) and

high (7.4) treatments (Table 2.14). For the 10 to 20 cm depth interval, the one-way ANOVA returned a significant P Value of 0.041 but Tukey's test was not able to determine a significant difference among treatments (Table 2.11), likely due to the large variation in sample values within treatments and the incorporation of the variance into the Tukey test. The general trend was a slight increase in pH with depth (Figure 2.7).

For Cell 46, pH for the 0 to 10 cm depth interval ranged from 4.2 to 7.7 for the low vegetation treatment and from 4.2 to 6.7 for the medium treatment. The low vegetation treatment (6.3) was significantly different from the medium (5.7) at this depth (Table 2.10) and for 20 to 40 cm interval the low vegetation treatment (7.1) was significantly different from the medium (6.8) (Table 2.13). Soil pH for the two vegetation treatments increased with depth (Figure 2.8).

Macyk et al. (1993) listed criteria for the evaluation of soil pH for the suitability of surface material for revegetation in the Northern Forest Region (Table 2.16). The pH values assigned to each category are the most appropriate for trees, primarily conifers. Since the end land use for Cells 32 and 46 is productive forestry, these values are appropriate to assess the results of this study. Three categories of suitability and one of unsuitable soils were used. The four categories are defined below.

Good: None to slight soil limitations that affect use as a plant growth medium.

Fair: Moderate soil limitations that affect use, but can be overcome by proper planning and good management.

Poor: Severe soil limitations that make use questionable. This does not mean the soil cannot be used, but careful planning and very good management are required.

Unsuitable: Chemical or physical properties of the soil are so severe reclamation would not be economically feasible or in some cases impossible.

According to Macyk's criteria for Cell 32, for the 0 to 10 cm depth interval, only four vegetation plots would rate good. The majority of low vegetation treatments would rate poor and medium and high vegetation treatments would rate fair. These ratings support the statistical analyses of this study which showed the low vegetation treatment had significantly higher pH than medium and high vegetation treatments, perhaps indicating high pH may be having a negative effect on plant growth.

According to Macyk's criteria for the 10 to 20 and 20 to 40 cm depth intervals, a high proportion of low vegetation treatments would rate poor and the majority of medium and high vegetation treatments would rate fair. Although not statistically significant within treatments, the low vegetation had a higher pH supporting the conclusion for the 0 to 10 cm depth. No plots within all treatments, for all depths, received an unsuitable rating. For Cell 32, all of the vegetation plots, except one in the medium vegetation treatment, fell into the basic pH range categories for fair and poor classes.

According to Macyk's criteria, for Cell 46, for the 0 to 10 cm depth interval, 11 of the vegetation plots would rate good, 3 from the low and 8 from the medium. The majority of low vegetation treatments, for all three soil depths, rate fair. For the medium vegetation treatment for the 10 to 20 cm depth interval, the majority of vegetation plots would rate good and for the 20 to 40 cm depth interval rate fair. No plots within the two treatments, for all depth profiles, received an unsuitable rating. Similar to Cell 32, Cell 46 had vegetation plots within the basic pH range for the fair classification criteria.

In Cells 32 and 46, most of the vegetation plots fell into the fair rating class, meaning there were moderate soil limitations that affected use, but with proper management could be overcome. For Cell 32, the results of this study agree with Chaikowsky (2003) who found a similar pH range (5.4 to 8.5) in the topsoil and tending to more basic with depth. It was interesting that medium and high vegetation treatments had pH values that were more neutral and they had higher species richness than the low vegetation treatment which was more basic. This suggests pH may play an important role in plant community composition. Watkinson et al. (2001) found that soil pH was the most important variable that determined species richness in ground vegetation in woodlands under different grazing regimes. Species richness was highest between pH 5.0 and 7.5. This was also supported by Critchley et al. (2002) who found soil pH strongly related to species richness. Within a wide range of temperate grasslands, the highest species richness (>30 plants m^{-2}) occurred between pH 6 and 8 and at pH <6 or >8 species richness was low (<20 plants m^{-2}).

4.6 Soil Electrical Conductivity

For Cell 32, electrical conductivity for the 0 to 10 cm depth interval, ranged from 0.3 to 4.7 dS/m. The three vegetation treatments, low (1.4 dS/m), medium (1.0 dS/m) and high (1.0 dS/m) were not significantly different at this or any other depth interval (Table 2.9). For the low vegetation treatment, electrical conductivities were generally consistent with a decrease in depth to the tailings sand. For medium and high vegetation treatments there was a decrease for the 0 to 10 cm to the 10 to 20 cm depth interval, then a consistent increase to 50 cm and a decrease thereafter. In the tailings sand the medium vegetation treatment (1.2 dS/m) was consistent with that of the reclamation soil (1.2 dS/m), but for the high vegetation treatment the tailings sand (0.7 dS/m) was lower than the reclamation soil (1.0 dS/m) (Figure 2.9).

For Cell 46, electrical conductivity for the 0 to 10 cm depth interval ranged from 0.5 to 11.0 dS/m for the low vegetation treatment and from 0.6 to 6.0 dS/m for the medium. The low (3.2 dS/m) and medium (3.1 dS/m) vegetation treatments were not significantly different at this or any other depth intervals (Table 2.10). Values for the two vegetation treatments generally decreased with depth except for higher values at 30 cm (Figure 2.10).

According to Macyk's criteria the majority of vegetation plots within Cell 32, for all depths, rated good (Table 2.17). For Cell 46 the majority of vegetation plots rated good but unlike Cell 32 there were a higher proportion of vegetation plots rated fair or poor. In the tailings sand, for both cells, all plots rated good (Table 2.17).

These results are consistent with Chaikowsky (2003) who also found that electrical conductivity was not affecting the root zone on Cell 32. Although electrical conductivities were low, McKenzie (1994) suggested that even at 2 dS/m, growth in species desired on the reclaimed landscape may be reduced. White spruce and northwest poplar (*Populus deltoides* Marsh. x *Populus balsamifera* Bartr. cv.) may only achieve 91 and 90% relative annual growth. This is supported by Renault et al. (1998) who suggested that although salt tolerance in trees and shrubs has not been extensively studied, conifers are particularly susceptible to salt stress.

A greater concern is noted for Cell 46 where electrical conductivities were generally higher and may continue to increase with time in the soil. This is supported by Price (2004) who found that the water table on Cell 46 is within 1 m of the surface on

93% of the slope with electrical conductivities of 2.0 to 3.0 dS/m. The seepage water is also expected to increase in salinity over time because of the water recycling measure of Syncrude (Qualizza 2004). Coupled with the low topsoil depth and rooting characteristics of boreal vegetation, this could have serious implications for plant community development.

4.7 Sodium Adsorption Ration (SAR) and Saturation Percentage

For Cell 32, SAR for the 0 to 10 cm depth interval ranged from 0.2 to 26.5. The low vegetation treatment (4.3) was significantly different from the medium (2.2) and high (1.2) treatments (Table 2.9). The statistically significant differences can be attributed to the very high SAR in the low vegetation treatment (8.0, 14.3, 18.2 and 26.5). In contrast all plots in the high vegetation treatment had SAR < 1.2, except for one plot on the toe slope (14.0). Across all other depths, SAR for the three vegetation treatments was not significantly different. For the three vegetation treatments, SAR generally increased with depth until 60 to 80 cm then decreased (Figure 2.11). In the tailings sand the low treatment had a slight decrease in SAR while the medium and high treatments had increases.

For Cell 46, SAR for the 0 to 10 cm interval ranged from 0.9 to 18.3 for the low vegetation treatment and from 0.6 to 25.8 for the medium. The low vegetation treatment (4.9) was not significantly different from the medium (9.2) (Table 2.10). For the 10 to 20 cm depth interval, SAR ranged from 0.6 to 13.8 for the low vegetation treatment and from 1.0 to 26.8 for the medium. The low vegetation treatment (4.6) was significantly different from the medium (11.6) at this and all other depths (Table 2.12). For both vegetation treatments SAR increased with depth (Figure 2.12).

According to Macyk's criteria, for Cell 32, for the 0 to 10 cm depth interval, the majority of the vegetation plots from all treatments rate good (Table 2.18). However, 3 plots from the low vegetation treatment, 2 from the medium and 1 from the high rated unsuitable. For the other depth intervals the majority of vegetation plots, from all treatments, rated good, but with an increase in depth there is a slight increase in the number of plots that rated unsuitable in the low vegetation treatment.

For Cell 46, for the 0 to 10 cm depth interval, the low vegetation treatment rated good for the majority of plots but a higher number of medium treatment plots rated poor and unsuitable, continuing to increase to the 20 to 40 cm depth interval where 78% of plots in the medium vegetation treatments rated poor or unsuitable. The statistical difference for the 20 to 40 cm depth interval is highly significant and the SAR means of the two treatments were very different, 5.99 for low and 13.56 for the medium vegetation treatment (Table 2.13). For the low vegetation treatment, for the remaining depth intervals, results were consistent with those for the 0 to 10 cm depth interval (Table 2.18).

For the tailings sand in Cells 32 and 46 the majority of vegetation plots rated good (Table 2.18). The exception is the medium treatments in Cells 32 and 46 where the majority of treatments had poor ratings. No vegetation plots were assigned an unsuitable rating based on the stipulation that materials characterized by an SAR of 12 to 20 may be rated as poor, not unsuitable, if the texture is sandy loam or coarser and saturation percentage is less than 100% (Macyk et al. 1993). Because the material is tailings sand it qualifies under this statement. In assessing high SAR in sandy soils, soil physical properties may not be seriously affected by higher sodium but the levels of sodium present in the sandy soils may cause serious problems for vegetation (Leskiw 1998).

Saturation percentage is closely associated with SAR in soils of loam or finer texture (Leskiw 1998). As SAR increases, saturation percentage increases because with greater dispersion, greater amounts of water are needed to saturate the soil. Leskiw noted that high saturation percentages may also occur in non-sodic soils (SAR $\leq$ 4) if there is high organic matter. Such was the case in this study, especially on Cell 46.

For Cell 32, percent saturation for the 0 to 10 cm depth interval ranged from 30 to 164%. The three vegetation treatments, low (51%), medium (54%) and high (48%), were not significantly different (Table 2.9). Across all other depth intervals, the percent saturations for the three vegetation treatments were not significantly different. The general trend was an increase with depth to the tailings sand then a decrease (Figure 2.13)

For Cell 46, percent saturation for the 0 to 10 cm depth interval ranged from 37 to 210% for the low vegetation treatment and from 69 to 250% for the medium treatment. The low (102%) was significantly different from the medium vegetation treatment (153%) (Table 2.10). For the 20 to 40 cm interval the low (85%) was also significantly

different from the medium vegetation treatment (111%) (Table 2.13). This suggests there is a higher percentage of peat at these depth intervals in the medium treatments.

The results are consistent with Chaikowsky (2003) who also found SAR was not severely affecting the root zone on Cell 32. However, the results from Macyk and Faught (2001) suggest SAR may be increasing in the soil above the tailings sand at a study site north of Cell 32 on the SWSS. In the four years of their study, seepage water analysis has shown SAR increased four-fold and they concluded tailings water is impacting the reclamation soil particularly immediately above the tailings sand. Thus over time SAR may increase in the reclamation soil and problems could occur, if these conditions occur.

For Cell 46 the medium vegetation treatment was not expected to have a higher SAR than the low treatment. The high SAR in the medium vegetation treatments may have resulted from the drier than average conditions from the time of reclamation on the cell and the plants establishing in areas with increased moisture availability. Increased moisture at the surface may be due to the interactions of the low soil depths and the high water table (tailings water). Plants would preferentially establish in areas with soil moisture rather than areas devoid of water even if they had higher sodium. As hypothesized with Cell 32, Cell 46 may have increased SAR in the reclamation soil over time and SAR may increase above tolerance limits of the established vegetation.

4.8 Cations

For Cell 32, sodium for the 0 to 10 cm depth interval ranged from 9 to 954 mg/L. The low vegetation treatment (162 mg/L) was significantly different from the high (45 mg/L) but not the medium (72 mg/L) (Table 2.9). In the tailings sand the high vegetation treatment (101 mg/L) was significantly different than the medium (204 mg/L) and low (124 mg/L) treatments (Table 2.15). Sodium in the low vegetation treatment generally decreased with depth until the 40 to 60 cm depth interval where concentration increased, then decreased through to the tailings sand (Figure 2.15). In the medium vegetation treatment sodium increased to the 60 to 80 cm depth interval where it decreased, then increased again in the tailings sand. In the high vegetation treatment sodium gradually increased throughout the profile with a decrease in the tailings sand.

For Cell 46, sodium for the 0 to 10 cm depth interval ranged from 198 to 2840 mg/L for the low vegetation treatment and from 28 to 991 mg/L for the medium vegetation treatment. The low vegetation treatment (403 mg/L) was not significantly different from the medium (498 mg/L) (Table 2.10). Across all other depths sodium was not significantly different except for the 20 to 40 cm depth interval where the medium (566 mg/L) was significantly higher than the low (333 mg/L) (Table 2.13). In general there was a decrease in sodium with depth (Figure 2.16).

For Cell 32, magnesium for the 0 to 10 cm depth interval ranged from 4 to 148 mg/L. The low (33 mg/L), medium (29 mg/L) and high (37 mg/L) treatments were not significantly different at this or all other depths (Table 2.9). In general there was a decrease in magnesium with depth (Figure 2.17).

For Cell 46, magnesium for the 0 to 10 cm depth interval ranged from 14 to 238 mg/L for the low vegetation treatment and from 16 to 94 mg/L for the medium. The low vegetation treatment (81 mg/L) was not significantly different from the medium (52 mg/L) at this or all other depths (Table 2.10). In general there was a decrease in magnesium with depth (Figure 2.18).

For Cell 32, calcium for the 0 to 10 cm depth interval ranged from 10 to 568 mg/L. The low (131 mg/L), medium (112 mg/L) and high (132 mg/L) were not significantly different at this or all other depth intervals (Table 2.9). The general trend for the low vegetation treatments was a decrease with depth until 60 to 80 cm where concentrations increased (Figure 2.19). The medium and high vegetation treatments had a decrease in concentration with depth to the 40 to 60 cm depth interval where concentrations increased then decreased again at the 60 to 80 cm depth interval. For all three treatments, there was a substantial decrease in concentrations in the tailings sand.

For Cell 46, calcium for the 0 to 10 cm depth interval ranged from 53 to 675 mg/L for the low and from 48 to 459 mg/L for the medium vegetation treatment. The low vegetation treatment (300 mg/L) was not significantly different from the medium (180 mg/L) at this or any other depth interval (Table 2.10). The general trend for the two vegetation treatments was a decrease with depth to the 20 to 40 cm interval where both treatments increased (Figure 2.20). For both treatments there was a substantial decrease in the tailings sand compared to the overlying reclamation soil.

The major influence of sodium, magnesium and calcium is in relation to SAR. For Cell 32 the higher concentration of sodium at the 0 to 10 cm depth interval was directly responsible for the higher SAR in the low vegetation treatment. The lower concentration of sodium in the tailings sand, lead to a lower SAR for the high vegetation treatment. Sodium may also be harmful to plant growth where chloride and sulphate form NaCl and Na_2SO_4 salts. Greenway and Munns (1980) suggested that the main consequences of plant exposure to these salts were water deficit and ion toxicity. This is supported by Redfield and Zwiazek (2002) who found that for black spruce seedlings treated with NaCl and Na_2SO_4 salts, injury to seedlings was largely caused by osmotic stress. They suggested drought tolerance parameters may be helpful in predicting salt tolerance of plants selected for revegetation of oil sands tailings.

4.9 Anions

For Cell 32, chloride for the 0 to 10 cm depth interval ranged from 14 to 1270 mg/L. The three vegetation treatments, low (372 mg/L), medium (127 mg/L) and high (148 mg/L), were not significantly different at this or any other depth interval (Table 2.9). The general trend for the low vegetation treatment was a decrease in concentration with depth (Figure 2.21). For the medium and high vegetation treatments concentrations decreased with depth until the 20 to 40 cm depth interval where they increased, then decreased for the 60 to 80 cm depth interval and increased again in the tailings sand.

For Cell 46, chloride for the 0 to 10 cm depth interval ranged from 17 to 2690 mg/L for the low and from 31 to 928 mg/L for the medium vegetation treatment. The low vegetation treatment (430 mg/L) was not significantly different from the medium (513 mg/L) at this or any other depth interval (Table 2.10). The general trend was a decrease in concentration with depth (Figure 2.22).

For Cell 32, sulphate for the 0 to 10 cm ranged from 17 to 2420 mg/L. The low vegetation treatment (372 mg/L) was significantly different from the medium (127.0 mg/L) and high (148 mg/L) treatments (Table 2.9). Across all other depths, concentrations for the three vegetation treatments were not significantly different. The general trend for the low vegetation treatment was a decrease in concentration with depth until 40 to 60 cm where it increased (Figure 4.23). Concentration increased again at 60 to

80 cm then decreased in the tailings sand. For medium and high vegetation treatments concentrations increased with depth until 60 to 80 cm then decreased to the tailings sand.

For Cell 46, sulphate for the 0 to 10 cm depth interval ranged from 198 to 2840 mg/L for the low and from 143 to 2320 mg/L for the medium vegetation treatment. The low (1194 mg/L) was not significantly different from the medium (871 mg/L) treatment at this or any other depth interval (Table 2.10). The general trend for both treatments was a consistent concentration in the reclamation soil with a decrease in the tailings sand (Figure 4.24).

4.10 Soil Macro-Nutrients

For Cell 32, water soluble potassium for the 0 to 10 cm depth interval ranged from 1 to 34 mg/L (Table). The low vegetation treatment (7 mg/L) was significantly different from the medium (12 mg/L) and high (10 mg/L) treatments (Table 2.9). This significant result was repeated in the 60 to 80 cm depth interval where the low (5 mg/L) and medium (4 mg/L) treatments were significantly different from the high (3 mg/L) (Table 2.14). In the tailings sand, the low (5 mg/L) and medium (5 mg/L) treatments were significantly different from the high (4 mg/L) (Table 2.15). Across all other depths potassium was not significantly different for the three vegetation treatments. The general trend was a decrease with depth, except for the medium and high treatments which had higher concentrations in tailings sand compared to overlying reclamation soil (Figure 2.25).

For Cell 46, water soluble potassium for the 0 to 10 cm depth interval ranged from 1 to 15 mg/L for the low and from 4 to 16 mg/L for the medium vegetation treatment. The low vegetation treatment (6 mg/L) was significantly different from the medium (8 mg/L) (Table 2.10). Across all other depths, concentrations were not significantly different. The general trend in the low treatment was a fairly consistent value (Figure 2.26). For the medium treatment concentration decreased with depth until the tailings sand where it increased compared to the overlying soil.

For Cell 32 water soluble nitrate and nitrite for the 0 to 10 cm depth interval ranged from below the detectable limit to 1.1 mg/L (Table 2.9). The low (0.1 mg/L) was not significantly different from the medium (0.1 mg/L) and high (0.1 mg/L) vegetation

treatments (Table 2.8). There was a significant difference at 40 to 60 and 60 to 80 cm depth intervals where the low vegetation treatment had marginally higher concentrations (Tables 2.15 and 2.16). Overall, nitrate and nitrite were low with many plots having concentrations below the detectable level of 0.2 mg/L. The results of this study are consistent with Chaikowsky (2003) who also found nitrogen was deficient on Cell 32 in 2001.

For Cell 46, nitrate and nitrite for the 0 to 10 cm depth interval ranged from below the detectable limit to 0.4 mg/L for the low and from below the detectable limit to 0.3 mg/L for the medium vegetation treatment. The low vegetation treatment (0.1 mg/L) was not significantly different from the medium (0.0 mg/L) at this or any other depth interval (Table 2.10). As with Cell 32 nitrate and nitrite were low with many plots having concentrations below the detectable level.

For Cell 32 water soluble phosphorus for the 0 to 10 cm depth interval ranged from below the detectable limit to 4 mg/L. The three vegetation treatments (0 mg/L) were not significantly different at this or any other depth interval (Table 2.9). For Cell 46, for the 0 to 10 cm depth interval, the low vegetation treatment did not have any plots above the detectable limit of 1 mg/L and the medium treatment ranged from below the detectable limit to 3 mg/L. The low and medium vegetation treatments (0 mg/L) were not significantly different at this or at any other depth interval (Table 2.10). As with nitrate and nitrite, phosphorus was low, with many plots having concentrations below the detectable level. For Cell 32 the results of this study are consistent with Chaikowsky (2003), who also found phosphorous was deficient on Cell 32 in 2002.

4.11 Soil Micro-Nutrients and Organic Carbon

For Cell 32, organic carbon for the 0 to 10 cm depth interval ranged from 0.3 to 12.0% and organic matter ranged from 0.6 to 22.0%. The three vegetation treatments were not significantly different for organic carbon, organic matter and micronutrients copper, iron, manganese and zinc (Table 2.9). For the 10 to 20 cm depth interval organic carbon ranged from 0.4 to 12.0% and organic matter ranged from 0.6 to 22.0%. The three vegetation treatments did not differ in organic carbon, organic matter or the micronutrients copper, manganese and zinc (Table 2.11). Iron for the low vegetation

treatment (31 mg/kg) was significantly different from the medium (69 mg/kg) and high (51 mg/kg) treatments.

For Cell 46, organic carbon for the 0 to 10 cm depth interval ranged from 1.1 to 11.0% for the low and from 7.4 to 12.0% for the medium vegetation treatment. Organic matter ranged from 1.9 to 30.0% for the low and from 13.0 to 28.0% for the medium vegetation treatment. The two vegetation treatments were significantly different for organic carbon, organic matter and micronutrients iron, manganese and zinc (Table 2.10). For the 10 to 20 cm organic carbon ranged from 1.5 to 11.0 % for the low and 6.5 to 12.0% for the medium vegetation treatment. Organic matter ranged from 2.6 to 56.0% for the low and 1.4% to 32.0% for the medium vegetation treatment. The two vegetation treatments were significantly different for organic carbon and micronutrients manganese and zinc (Table 2.12).

According to AAFRD (2002a) guidelines for micronutrients in agricultural soils (Table 2.19), micronutrient deficiencies existed on Cell 32, for the 0 to 10 cm depth interval (Table 2.20). The numbers of vegetation plots classified as copper deficient were 6 in the low, 1 in the medium and 2 in the high vegetation treatments. For manganese only the low vegetation treatment had plots classified as deficient. Zinc had the greatest number of deficient sites: 16 in the low, 7 in the medium and 7 in the high vegetation treatments. No sites, within all vegetation treatments, were classified as iron deficient.

Micronutrient deficiencies also occurred for the 10 to 20 cm depth interval for Cell 32. The numbers of vegetation plots classified as copper deficient were 8 in the low, 2 in the medium and 1 in the high vegetation treatments. The low and medium vegetation treatments had 1 plot classified as manganese deficient. Zinc had the greatest number of deficient plots, with 15 in the low, 14 in the medium and 10 in the high vegetation treatments. Although there was a statistically significant difference for iron between vegetation treatments, these guidelines suggest there would not be a significant biological difference as no sites within all vegetation treatments were classified as deficient.

According to AAFRD (2002a) guidelines there were micronutrient deficiencies on Cell 46, for the 0 to 10 cm depth interval (Table 2.18). Vegetation plots classified as copper deficient were 2 in the low and 3 in the medium vegetation treatments. For zinc, the guidelines support the statistically significant difference between vegetation

treatments. The low vegetation treatment had 5 sites classified as deficient while the medium treatment had none. Although there was a statistically significant difference for iron and manganese between vegetation treatments, these guidelines suggest there would not be a significant biological difference. For iron and manganese no sites within the two vegetation treatments were classified as deficient.

There were micronutrient deficiencies for the 10 to 20 cm depth interval for Cell 46. The number of vegetation plots classified as copper deficient was 1 in the low and 1 in the medium vegetation treatments. For zinc, the guidelines would support the statistically non significant difference found between vegetation treatments as each treatment had 4 sites classified as deficient. Again the statistically significant effect for iron and manganese between vegetation treatments would not be evident by the application of these guidelines. Each vegetation treatment would have no plots classified as iron deficient and 1 plot classified as manganese deficient.

In summary, the greatest number of vegetation plots classified as deficient occurred in the low vegetation treatment and the lowest numbers occurred in the high vegetation treatment. Initially the results for micronutrient deficiencies were not expected, as the vegetation survey found few quadrats with any signs of poor plant health and micronutrient deficiencies. Caution must be used in applying these guidelines as they were developed for agricultural soils where demands upon soil micronutrients are greater. In natural ecosystems, micronutrients are recycled within the system whereas within agricultural systems micronutrients are removed from the soil through crop harvest (Soon 1994). Therefore, agricultural soils under annual cropping regimes would require more soil micronutrients. This classification is also general and micronutrients vary between soil type and their requirements differ for plant species.

When soil organic matter is considered, the micronutrient results of this study were expected. AAFRD (2002a) suggested soil organic matter contains micronutrients in both plant unavailable and available forms and a fine balance exists between soil organic matter and micronutrients. Soils with <2% organic matter usually do not hold enough micronutrients to satisfy plant requirements. Within Cell 32, 18 vegetation plots or 27% of plots had <2% organic matter and within Cell 46, 2 vegetation plots had <2% organic matter and all 20 plots were from the low vegetation treatment. At >30% organic matter,

soils can also have low plant available micronutrients because organic matter can tie up the micronutrients on exchange sites and thus convert them to plant unavailable forms (AAFRD 2002a). In particular, copper becomes less available as soil organic matter content increases. Cell 32 had no site with >30% organic matter and Cell 46 had 3 such sites, 2 of which were classified as low vegetation. Similar conclusions were made by Sakal et al. (1998) who found organic matter highly correlated to the levels of available zinc, copper, iron and manganese within the soil.

A greater concern is noted when combining soil pH and micronutrient availability. For Cell 32 a large majority of low vegetation plots were classified, within the basic range, as poor (pH 7.5 to 9.0). With a higher pH, iron, manganese, copper and zinc form metallic cations that precipitate and are unavailable for plant use (Troeh and Thompson 1993). With the application of AAFRD (2002a) guidelines, it is evident that low vegetation treatments were classified as deficient for copper and zinc and coupled with the high pH, may lead to serious problems for plant establishment and community growth.

Within Cell 46 problems associated with pH, micronutrients and plant growth may be reversed as micronutrient toxicity may be a problem. Although the majority of vegetation plots were classified as fair, some were in the pH range of 4.0 to 5.0. Within this range and lower, the solubility of manganese, iron and zinc increase and toxicity may be a problem (Troeh and Thompson 1993, Larcher 2002). The AAFRD (2002a) guidelines suggest manganese and iron would not be in short supply and thus toxicity could lead to problems for plant health and survival. Species, such as blueberry (*Vaccinium myrtilloides* Michx.) and strawberry (*Fragaria virginiana* Duchesne), both desired on the reclaimed landscape, are classified as iron loving plants and would prosper in soils with a pH between 5.0 and 6.0 (Troeh and Thompson 1993).

4.12 Species Richness, Relative Canopy Cover and Indicator Species

Within Cell 32 there was a total of 35 plant species or groups. The low vegetation treatment (5 species per plot) was significantly different for species richness from the medium and high (8 species per plot) (Table 2.22). The top five species in relative canopy cover were sweetclover (*Melilotus* spp.) (24%), perennial sow thistle (*Sonchus*

arvensis L.) (23%), fireweed (*Epilobium angustifolium* L.) (20%), dandelion (*Taraxacum officinale* Weber) (9%) and common horsetail (*Equisetum arvense* L.) (7%) (Table 2.23). The indicator species analyses denoted that sweetclover, slender wheatgrass (*Agropyron trachycaulum* (Link) Malte (*A. trachycaulum* var. *trachycaulum*)), fireweed, common horsetail, perennial sow thistle, wild red raspberry (*Rubus idaeus* L.) and northern wheatgrass (*Agropyron dasystachyum* (Hook.) Scribn.) each had importance values that were significantly higher in the high vegetation treatment (Table 2.24). Ticklegrass (*Agrostis scabra* Willd.) had significantly higher importance in the medium vegetation treatment. As expected there were no indicator species in the low vegetation treatment.

For Cell 46 there was a total of 31 plant species or groups. The low vegetation treatment (4 species per plot) was significantly different for species richness from the medium treatment (8 species per plot) (Table 2.22). The top five species in relative canopy cover were bluejoint (*Calamagrostis canadensis* (Michx.) Beauv.) (31%), perennial sow thistle (24%), fireweed (10%), common horsetail (9%) and common yarrow (*Achillea millefolium* L.) (3%) (Table 2.25). The indicator species analyses indicated that bluejoint, sedge, perennial sow thistle, common yarrow, wild vetch (*Vicia americana* Muhl.), coltsfoot (*Tussilago* spp.) and long-leaved chickweed (*Stellaria longfolia* Muhl.) had importance values that were significantly higher in the medium vegetation treatment (Table 2.24). As expected, there were no indicator species in the low vegetation treatment.

Given the characteristics of sweetclover, it is not surprising that it had the highest relative canopy cover and was the most important indicator species on Cell 32. It is a pioneer species adapted to a wide range of soil textures, has very low nutrient requirements and is very aggressive and competitive (Hardy BBT Ltd. 1989). Wolf et al. (2004) suggested that the opportunistic *Melilotus* spp. possess characteristics that make them very competitive. They colonize disturbed areas, produce a large number of seeds, grow early in the season to create a tall dense colony, produce extensive root systems and fix nitrogen for their immediate use. Skousen (1988) reported that the pH tolerance range of sweet clover is between 6.0 to 8.0, it is salt tolerant within electrical conductivies of 3 to 5 dS/m (Evans and Kearney 2003) and performs well within a soil organic matter range of 1.60 to 10.74% (Wolf et al. 2004), which are all within the ranges found in this

study. Contrary to the results of this study, Fedkenheuer and Langevin (1978) reported that sweetclover had poor performance in seeding trials for the revegetation of tailings and thus was eliminated from seed mixes.

Given the characteristics of bluejoint it is also not surprising that it had the highest relative canopy cover and was the most important indicator species on Cell 46. It is described as an early successional and an aggressive pioneer species of disturbed sites (Hardy BBT Ltd. 1989). It is generally found on moist sites, can grow well on peat soils and is tolerant of low soil pH. Although bluejoint is native to North America, its performance on the reclaimed landscape and its ability to suppress the establishment of desired tree species are of concern. Landhausser and Lieffers (1998) suggested that aspen can exhibit significantly reduced total biomass, plant height and root collar calliper under direct competition with bluejoint. Hangs et al. (2002) also showed that bluejoint can suppress the growth of white spruce and jack pine. Coupled with the high persistence of bluejoint, it could limit the establishment of desired tree species on the reclaimed landscape.

The other dominant species on Cells 32 and 46 can all be described as early successional pioneer species common to disturbed lands. Perennial sow thistle is listed as a noxious weed in Alberta under the Alberta Weed Control Act (AAFRD 2002b). Dandelion is listed as a nuisance weed in Alberta under the Alberta Weed Control Act.

The indicator species analysis has shown that the important species on Cell 32 are not just common weeds and that desired species native to North America were present with high frequency and abundance. Slender wheatgrass was the second most important species in the high vegetation treatments and is common to the boreal forest, has high tolerance to soil salinity and performs well under cool climates (Hardy BBT Ltd. 1989). It is also tolerant of a variety of nutrient regimes and Rowell (1977) suggested that it has good performance on tailings sand at lower fertilization rates possibly because of poorer success of other species and reduced competition. Northern wheatgrass, ticklegrass and wild red raspberry are also native to Native America and are desired species on the reclaimed landscape. They are adapted to a wide range of soil textures and can tolerate low nutrient regimes and a variety of soil pH ranges (Hardy BBT Ltd. 1989). For Cell 46 the indicator species analyses suggested that wild vetch, another species native to North

America, is present at high frequency and abundance. It has importance in the reclaimed landscape as a nitrogen fixer and as forage for wildlife (Hardy BBT Ltd. 1989).

4.13 Ordination

4.13.1 Cell 32

For the NMS ordinations, the two axes explained 95.3% of the variation in the vegetation species community (Axis 1 R^2 = 88.6% and Axis 2 R^2 = 6.8%). Overall the ordination was very strong as it had 2 dimensions, a stress of 10.120 and a final instability of 0.00001.

For the 0 to 10 cm depth interval the NMS ordination confirmed differences between vegetation treatments (Figure 2.27). The majority of low vegetation treatments were located in the upper right quadrat while the medium and high vegetation treatments were mainly located in the lower left quadrat. The medium vegetation treatment was mainly associated to the right of the high treatment suggesting a position of neutrality between the other two treatments. The ground cover variables of bare ground and rocks were strongly associated with the low vegetation treatment and litter, live vegetation and moss were strongly associated with the medium and high treatments.

Lamb's quarters (*Chenopodium album* L.) and tufted hairgrass (*Deschampsia caespitosa* (L.) Beauv.) were associated with the low vegetation treatments while the remaining species were associated with the medium and high treatments. Lamb's quarters was expected to be associated with the low vegetation treatment as the indicator species analyses also showed it had a low vegetation treatment preference. Lamb's quarters had the highest significance (P = 0.670) in the species indicator analysis of the three species with the low treatment as a preference. The association of tufted hairgrass with the low vegetation treatment was not expected as the species indicator analysis indicated it had a preference for the high vegetation treatment (0.842). For the remaining species the results were expected as the indicator analysis suggested all but three species were associated with the medium and high vegetation treatments.

The results of the joint plot with soil chemical and physical parameters showed that SAR and sodium were associated closely with the low vegetation treatments and potassium was related to the medium and high vegetation treatments. The SAR result was

expected as it was also significantly different between the low and the medium and high vegetation treatments in the one way ANOVA. SAR is likely having an influence on plant community development. The sodium result was also expected as sodium is included in the SAR calculations. High SARs were likely due to the strong influence of increased sodium ions and not due to insufficient quantities of calcium and magnesium. Potassium's association with medium and high vegetation treatments was also expected as the one way ANOVA found a significant difference between the low vegetation treatment and the medium and high treatments. Coupled with the results of the indicator species analyses, potassium may be affecting the plant community structure. Slender wheatgrass is noted for having extremely reduced growth in potassium deficient soils (Hardy BBT Ltd. 1989), which may be why slender wheatgrass is dominant in the high vegetation treatments where the potassium concentration was greater.

For the 10 to 20 cm depth interval the NMS ordination joint plot was very similar to that for the 0 to 10 cm depth interval (Figure 2.28). The difference is that potassium was not associated with medium and high vegetation treatments and chloride was also associated with low vegetation treatments. Potassium was not significantly different at this depth interval in the one way ANOVA and this is represented in the ordination. Although chloride was not significantly different in the one way ANOVA it had a correlation with the low vegetation treatment. The difference between the two statistical methods could be explained by the blocking factor in the one way ANOVA that is not present within the NMS ordination. Chloride concentrations were significantly higher in the toe slope ($p = 0.000$) compared to the other four slopes and this variation was excluded in the one way ANOVA with the blocking factor of slopes. Within the ordination, the slopes were not separated or blocked and this variation within the toe slope was responsible for chloride being associated with the low vegetation treatment within the ordination.

4.13.2 Cell 46

The NMS ordination for the 0 to 10 cm depth interval found that the two axes explained 95.3% of the variation in the vegetation species community (Axis 1 $R^2 = 8.5\%$

and Axis 2 R^2 = 86.8%). Overall the ordination was very strong as it had 2 dimensions, a stress of 8.746 and a final instability of 0.00000.

The NMS ordination confirmed differences between low and medium vegetation treatments (Figures 2.29). The low vegetation plots were located mainly in the lower left quadrat while the medium plots were mainly located in the upper right quadrat. The ground cover variables of bare ground and rocks were strongly associated with the low vegetation treatment and litter, live vegetation and moss were strongly associated with the medium treatments.

Lamb's quarters, horsetail (*Equisetum sciropides* Michx.) and fowl bluegrass (*Poa palustris* L.) were associated with low vegetation treatments while the remaining species were associated with medium vegetation treatments. The three species were expected to be associated with the low vegetation treatment as results of the indicator species analyses also showed they had a low vegetation treatment preference. Lamb's quarters had the highest significance (P = 0.229) followed by horsetail (P = 0.479) and fowl bluegrass (1.000) in the species indicator analysis.

The results of the joint plot with soil chemical and physical parameters showed that pH and clay were associated more closely with low vegetation treatments and organic matter, zinc, iron, manganese, percent saturation and topsoil depth were related to medium vegetation treatment. For the low vegetation treatment, the association with pH is supported by the results from the one way ANOVA as there was a significantly higher pH for the low vegetation treatment. The association to clay is not supported by the results of the one way ANOVA which did not find a statistically significant difference between low and medium vegetation treatments. For the medium vegetation treatment the association with organic matter and zinc, iron and manganese were expected. Organic matter content and micronutrients were all significantly higher in the one way ANOVA for the medium vegetation treatment and this trend was represented in the NMS ordination. This also supports the correlation between organic matter and micronutrients discussed in section 4.11. It would follow that with higher organic matter, percent saturation would be higher in the medium treatment which explains the association with the medium vegetation treatment in the NMS ordination. The reclamation soil depth was

also significantly greater in the one way ANOVA and this trend continued in the NMS ordination with its association with the medium vegetation treatment.

The NMS ordination for the 10 to 20 cm depth interval showed that the two axes explained 94.8% of the variation in the vegetation species community (Axis 1 R^2 = 74.4% and Axis 2 R^2 = 20.4%). Overall the ordination was very strong as it had 2 dimensions, a stress of 8.890 and a final instability of 0.00001.

Again the NMS ordination for the 10 to 20 cm depth interval confirmed differences between low and medium vegetation treatments (Figure 2.30). The low vegetation plots were located in the upper left quadrat while the medium plots were located in the lower right quadrat. The ground cover variables of bare ground and rocks were strongly associated with the low vegetation treatment and litter, live vegetation and moss were strongly associated with medium and high vegetation treatments.

Lamb's quarters and horsetail were associated with low vegetation treatments while the remaining species were associated with medium vegetation treatments. The difference between the 0 to 10 cm and the 10 to 20 cm depth intervals is the removal of fowl bluegrass from the matrix in the 10 to 20 cm depth interval as it occurred in the two plots removed from the 10 to 20 cm depth interval because of low reclamation soil depth (see section 3.6).

The results of the joint plot with soil chemical and physical properties yielded similar results as the 0 to 10 cm depth interval except that calcium and magnesium were associated with low vegetation treatments and clay and pH were not. Also SAR, chloride and sodium were now associated with the medium treatments and reclamation topsoil depth was not. The results from the NMS ordination suggesting magnesium and calcium were associated with the low vegetation treatment and that sodium was associated with the medium treatment were not supported by the one way ANOVA, which indicated there was not a statistically significant difference between treatments. This suggests that when each parameter was treated as a separate entity no difference was found but the combination of the three parameters (SAR) yielded significant results, as evidenced by the association of SAR with the medium vegetation treatment. This is also supported by the result of the one way ANOVA that concluded a significantly higher SAR was present in the medium vegetation treatment at the 10 to 20 cm depth interval. The difference

between the two depth intervals and the exclusion of reclamation topsoil depth from the 10 to 20 cm NMS ordination could be explained by the removal of the two plots with the lowest reclamation topsoil depth (see section 3.6) and the resulting removal of this variation in the NMS ordination. The absence of clay from the 10 to 20 cm NMS ordination is because the measurement for soil texture was not made for the 10 to 20 cm depth interval and thus not included in the NMS ordination.

5.0 CONCLUSIONS

Plant communities on Cell 32 and 46 were comprised of early successional, ruderal species typically found on disturbed sites. These ruderal species comprised the majority of canopy cover on both cells. Sweetclover and bluejoint had the highest relative canopy covers on Cells 32 and 46, respectively. The high bluejoint cover on Cell 46 may impede the future establishment and growth of desired tree species which may limit future revegetation success.

Electrical conductivities were not statistically different among treatments on both cells. For Cell 32, the reclamation soil, on average, did not have electrical conductivities that were high enough to affect vegetation. On Cell 46 the average electrical conductivities on both treatments were high enough to theoretically affect vegetation (> 2dS/m). However, plant parameters measured did not show a vegetation response to these high values. This may be due to the interactions of higher organic matter and the buffering against higher electrical conductivities. In addition the majority of plant species established on Cell 46 had some degree of salt tolerance.

For Cell 32 poor plant community development was associated with higher sodicity, especially in the upper reclamation soil where statistical differences were found among vegetation treatments. SAR increased with depth across treatments suggesting that tailings water impacted or may be impacting the reclamation soil at depth. This may have implications in future years when vegetation has matured and the roots are penetrating deeper into the reclamation soil.

For both cells poor plant community development was associated with decreased concentrations of soil nutrients. For Cell 32, potassium was significantly lower within the low vegetation treatment and the NMS ordination identified it as having a strong

association with the medium and high vegetation treatments. Both cells had micronutrient deficiencies and the greatest number of zinc and copper deficient plots occurred in the low vegetation treatment. There may be secondary negative implications for plant community development as micronutrients combined with pH may affect micronutrient availability and perhaps toxicity.

On Cell 32 there was no association between plant community response and soil physical parameters. However, on Cell 46 the lowest canopy covers occurred in the plots that had the lowest topsoil depths. At the current stage of plant community development where roots are only in the top 30 cm, topsoil depths less than this are associated with poor plant response. Therefore, in future years when vegetation has developed greater rooting depths, these low topsoil depths may be a concern for future revegetation success.

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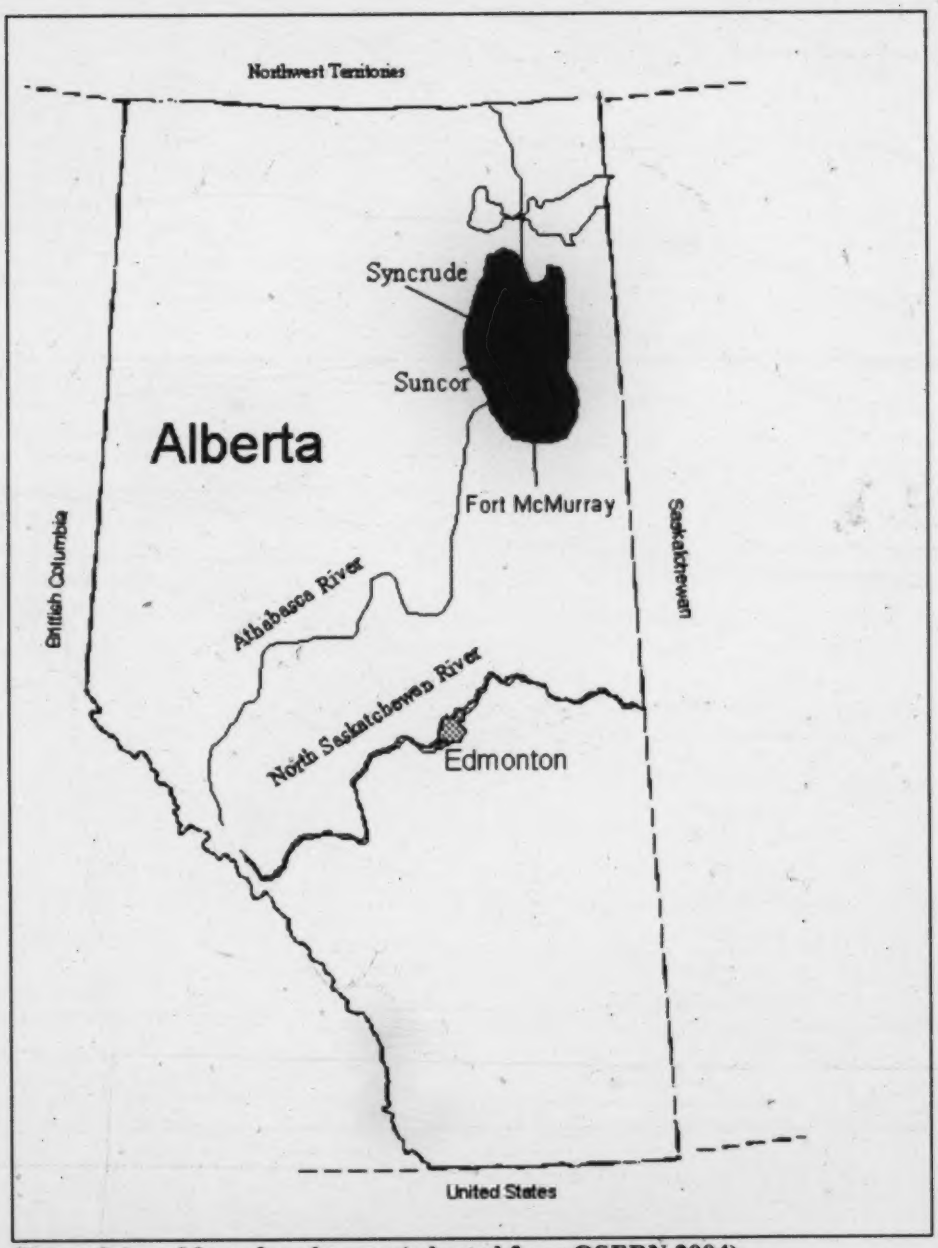

Figure 2.1 Map of study area (adapted from OSERN 2004)

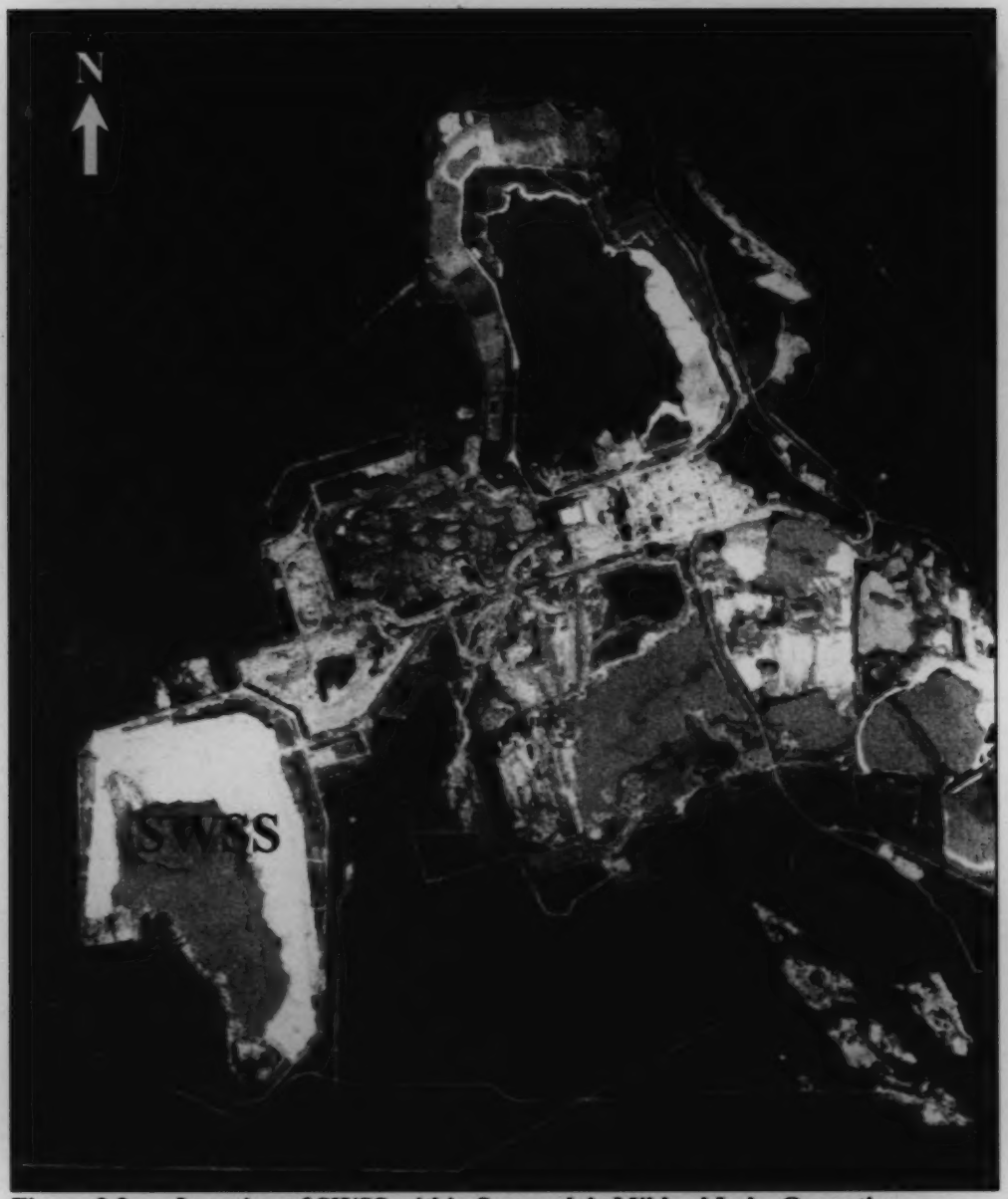

Figure 2.2 **Location of SWSS within Syncrude's Mildred Lake Operation (adapted from Syncrude Canada Ltd.)**

Figure 2.3 **Location of Cells 32 and 46 on the SWSS(adapted from Syncrude Canada Ltd.)**

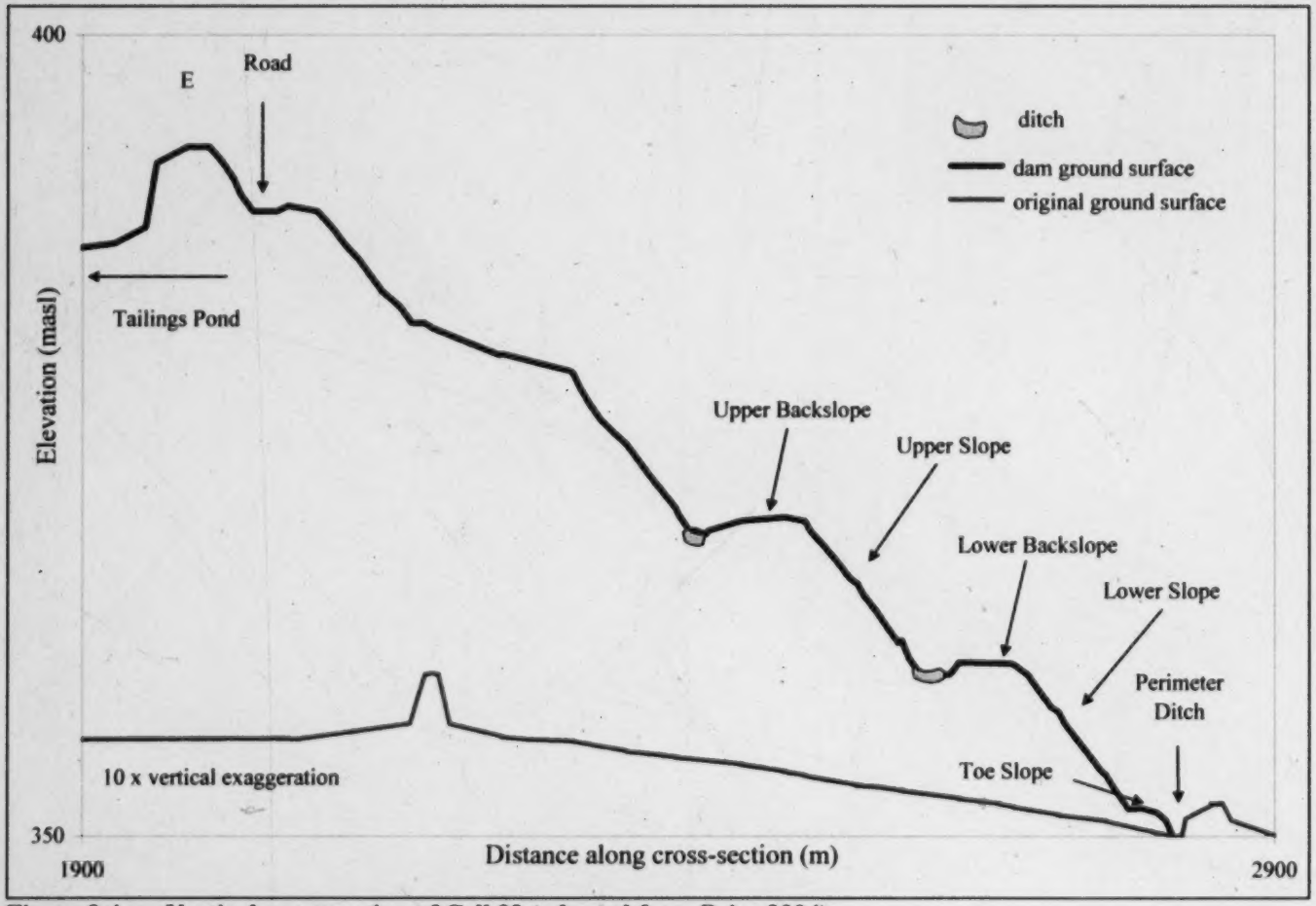

Figure 2.4 Vertical cross-section of Cell 32 (adapted from Price 2004)

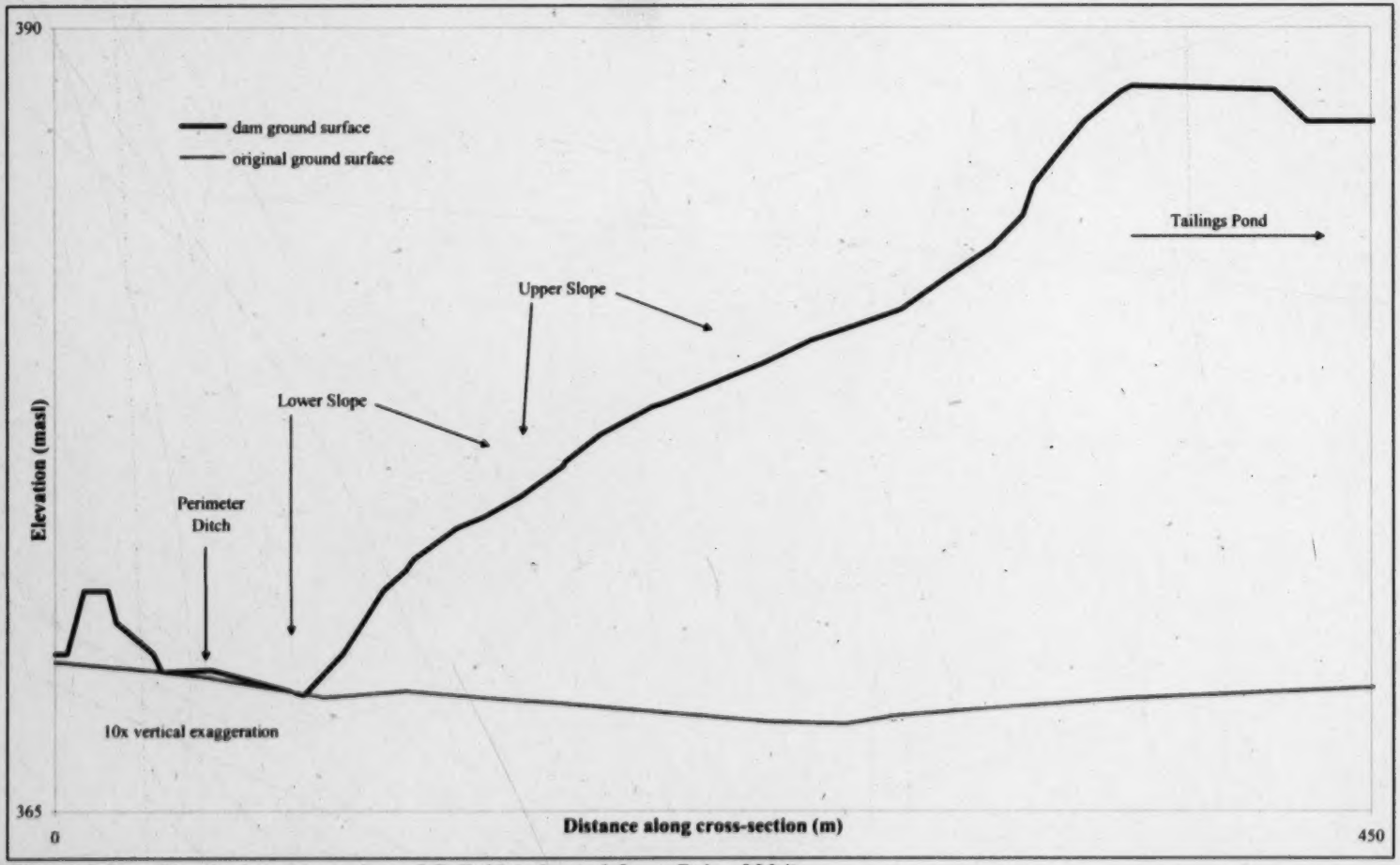

Figure 2.5 Vertical cross-section of Cell 46 (adapted from Price 2004)

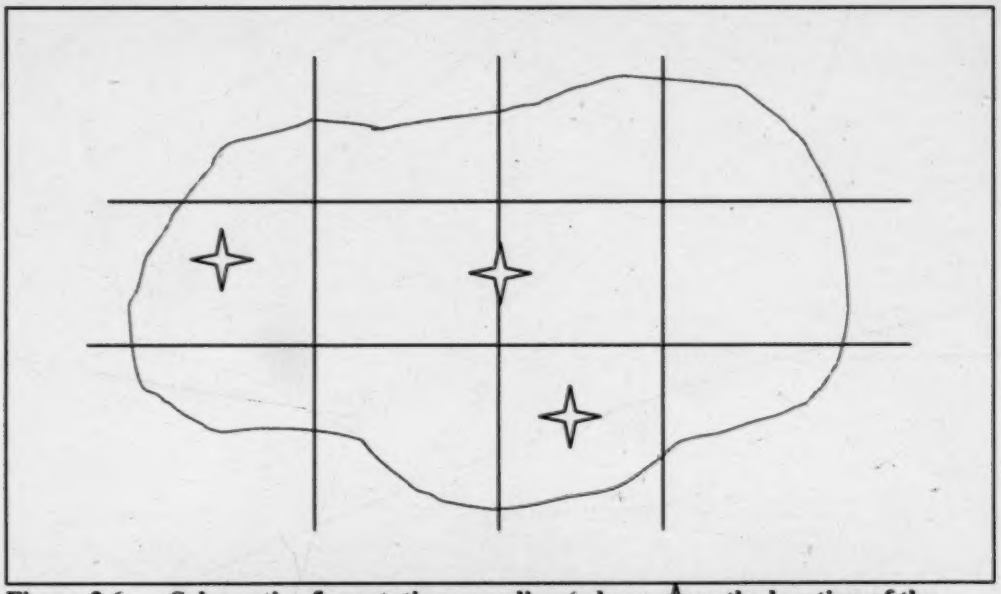

Figure 2.6 **Schematic of vegetation sampling (where ✦ = the location of the three quadrats assessed, one at the geographical center of each vegetation plot and two randomly located with 12 subdivided quadrats)**

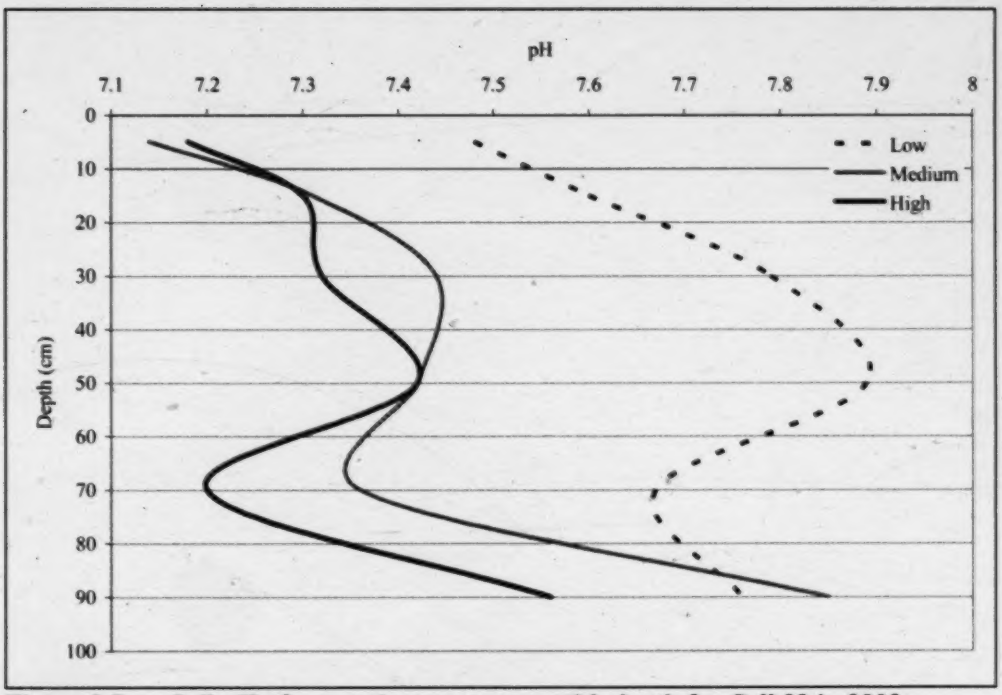

Figure 2.7 Soil pH of vegetation treatments with depth for Cell 32 in 2003

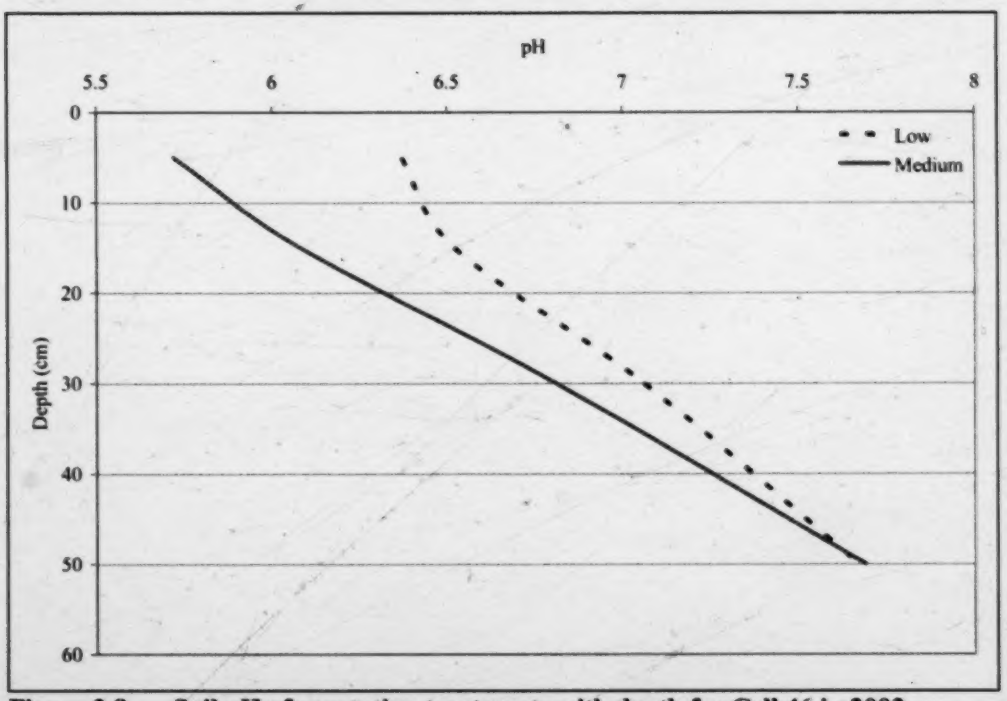

Figure 2.8 Soil pH of vegetation treatments with depth for Cell 46 in 2003

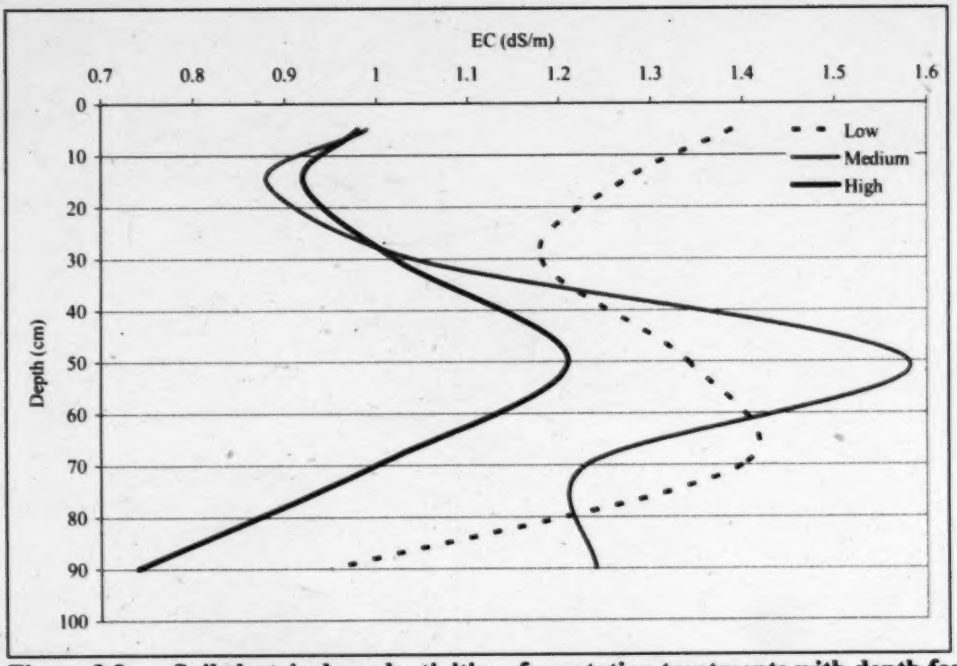

Figure 2.9 Soil electrical conductivities of vegetation treatments with depth for Cell 32 in 2003

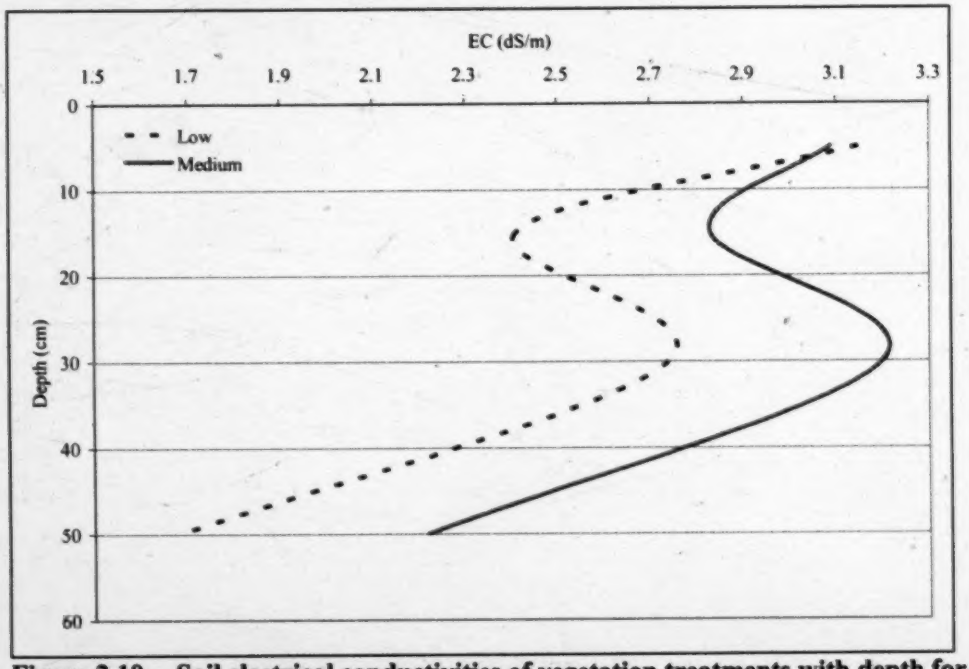

Figure 2.10 Soil electrical conductivities of vegetation treatments with depth for Cell 46 in 2003

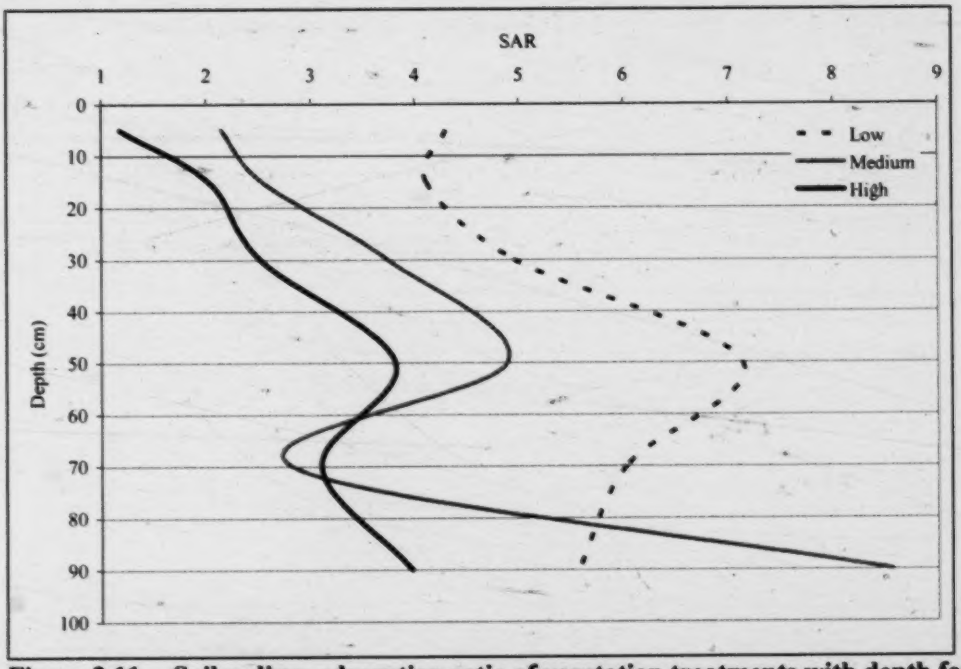

Figure 2.11 Soil sodium adsorption ratio of vegetation treatments with depth for Cell 32 in 2003

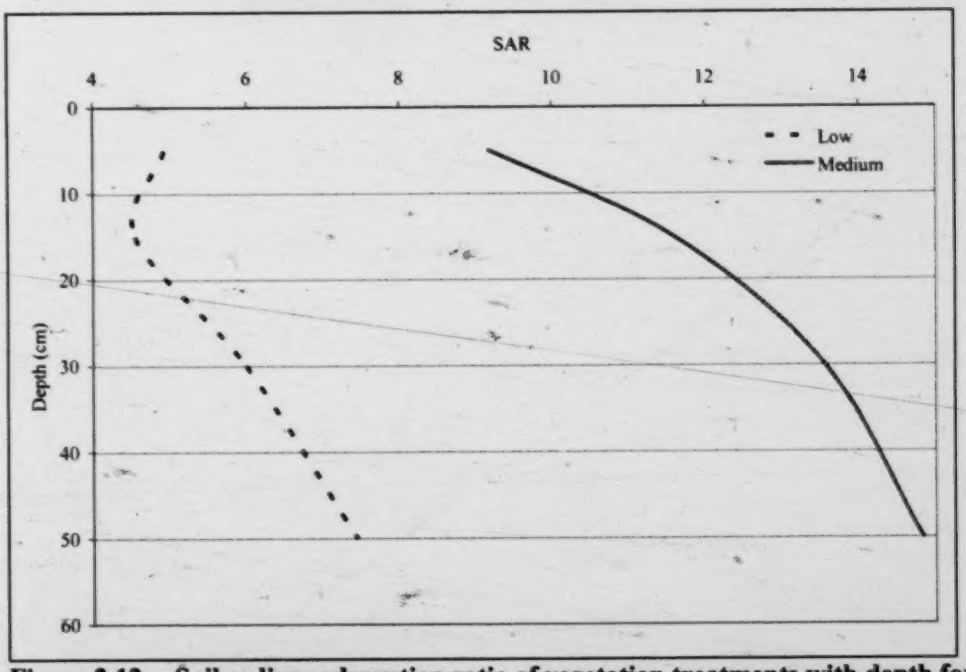

Figure 2.12 Soil sodium adsorption ratio of vegetation treatments with depth for Cell 46 in 2003

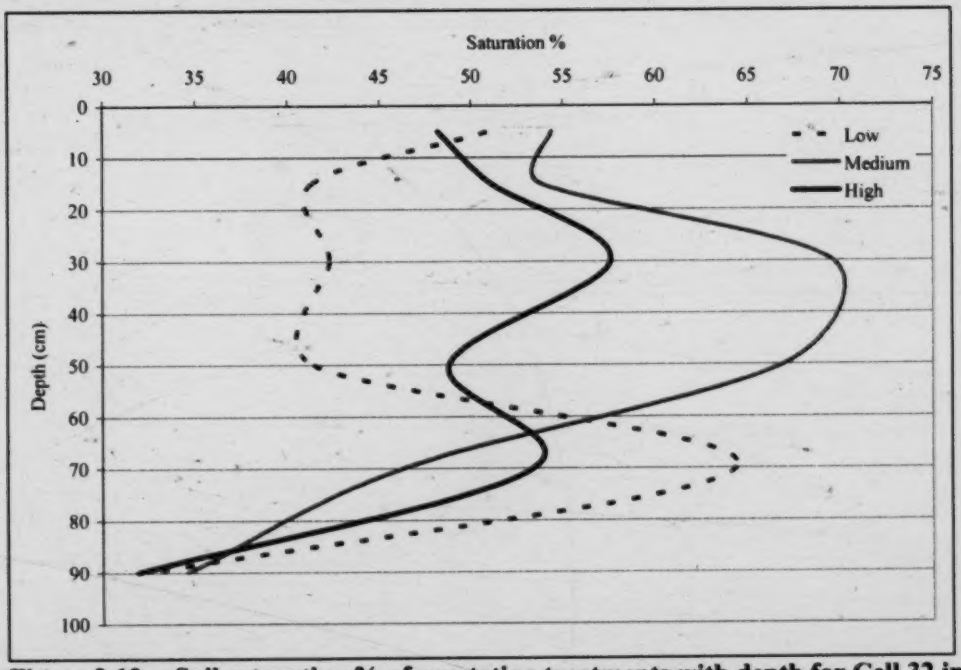

Figure 2.13 Soil saturation % of vegetation treatments with depth for Cell 32 in 2003

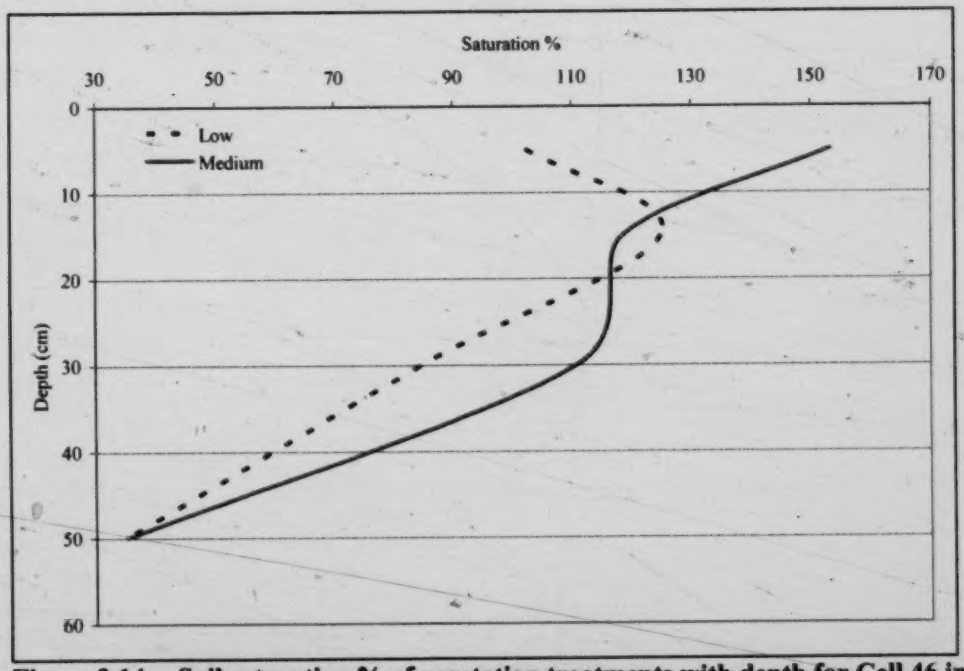

Figure 2.14 Soil saturation % of vegetation treatments with depth for Cell 46 in 2003

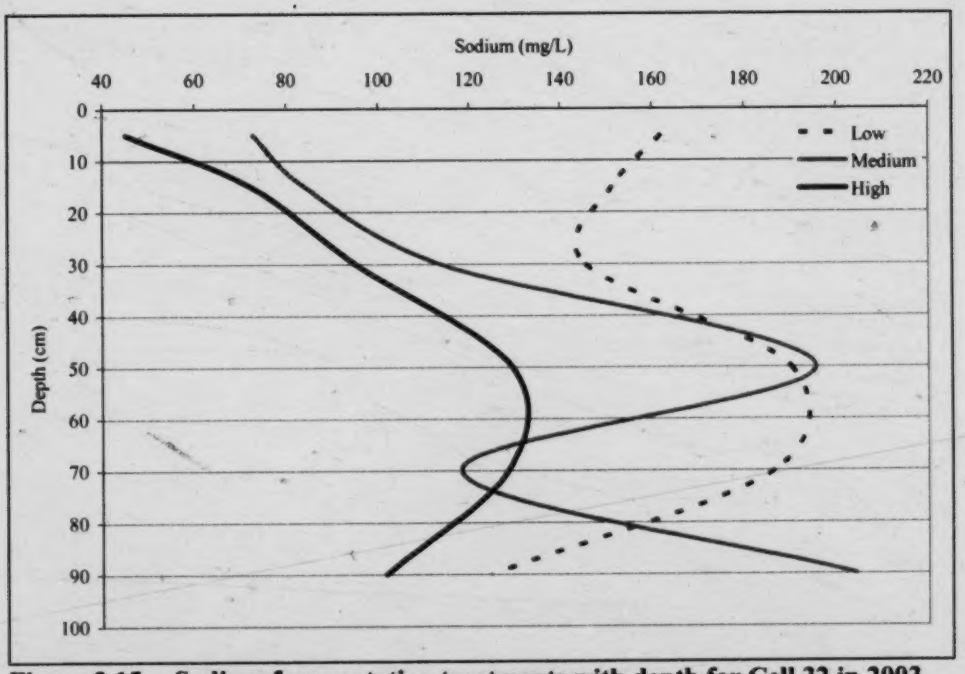

Figure 2.15 Sodium for vegetation treatments with depth for Cell 32 in 2003

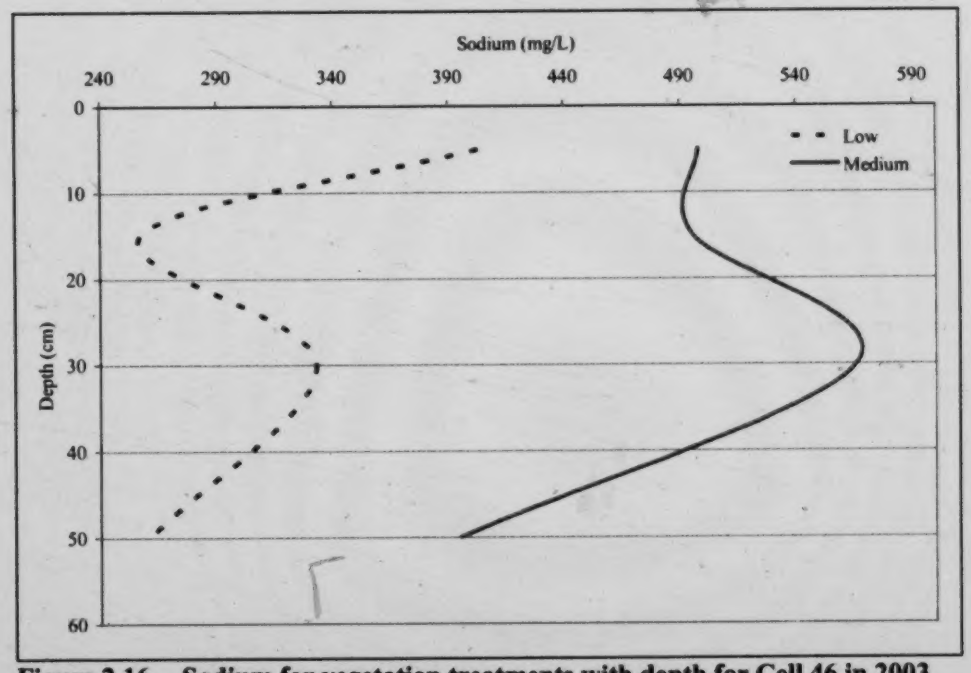

Figure 2.16 Sodium for vegetation treatments with depth for Cell 46 in 2003

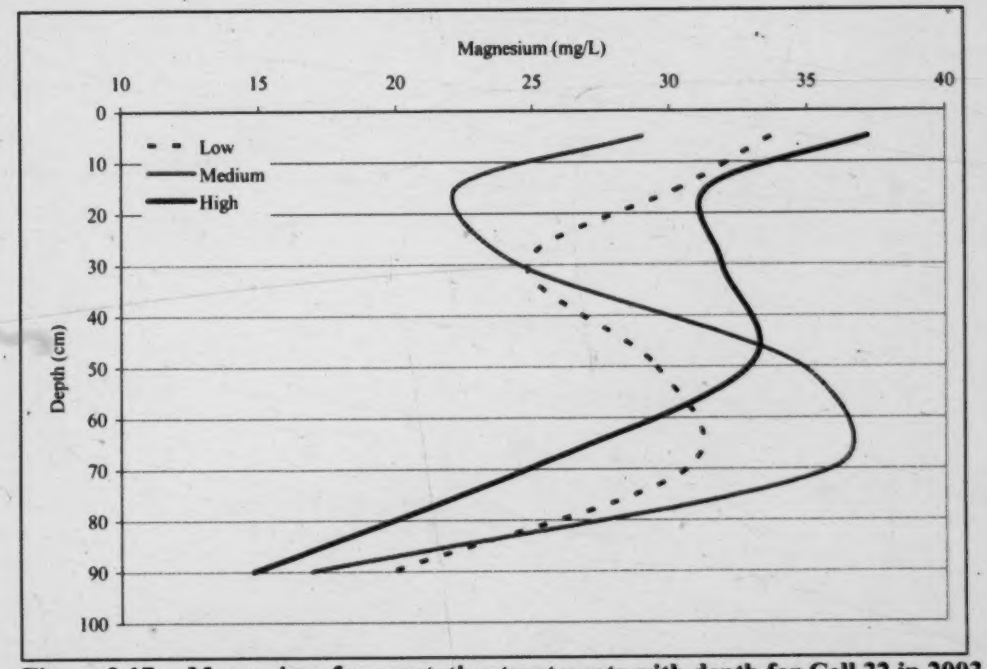

Figure 2.17 Magnesium for vegetation treatments with depth for Cell 32 in 2003

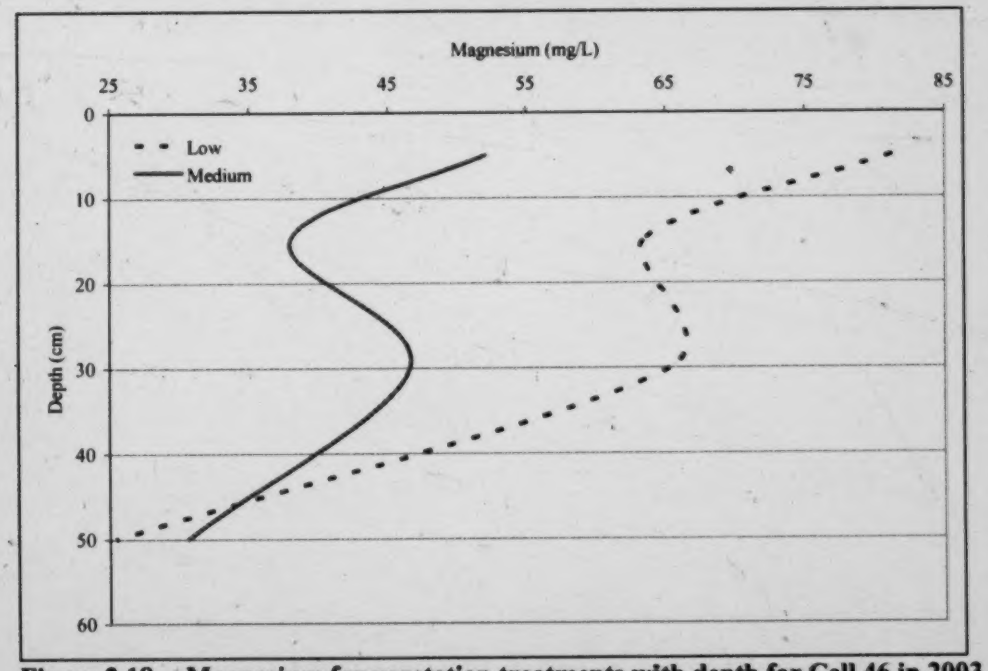

Figure 2.18 Magnesium for vegetation treatments with depth for Cell 46 in 2003

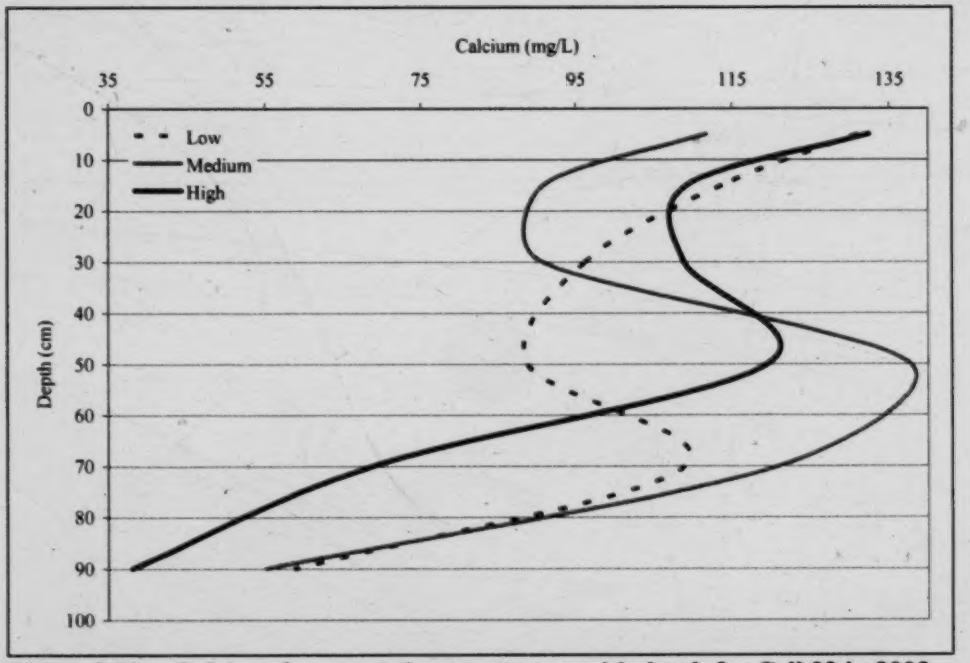

Figure 2.19 Calcium for vegetation treatments with depth for Cell 32 in 2003

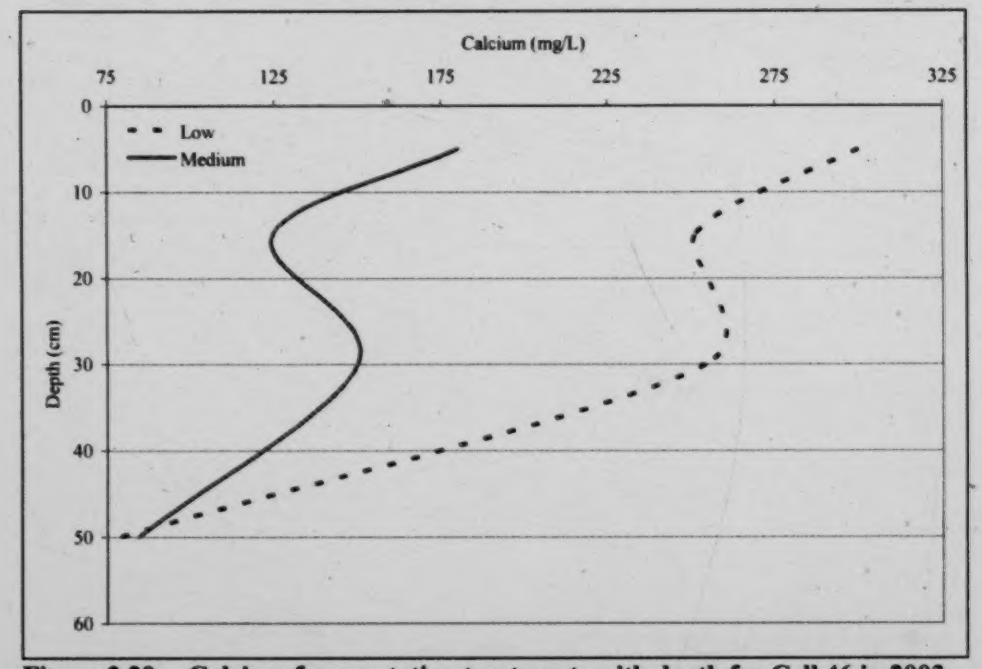

Figure 2.20 Calcium for vegetation treatments with depth for Cell 46 in 2003

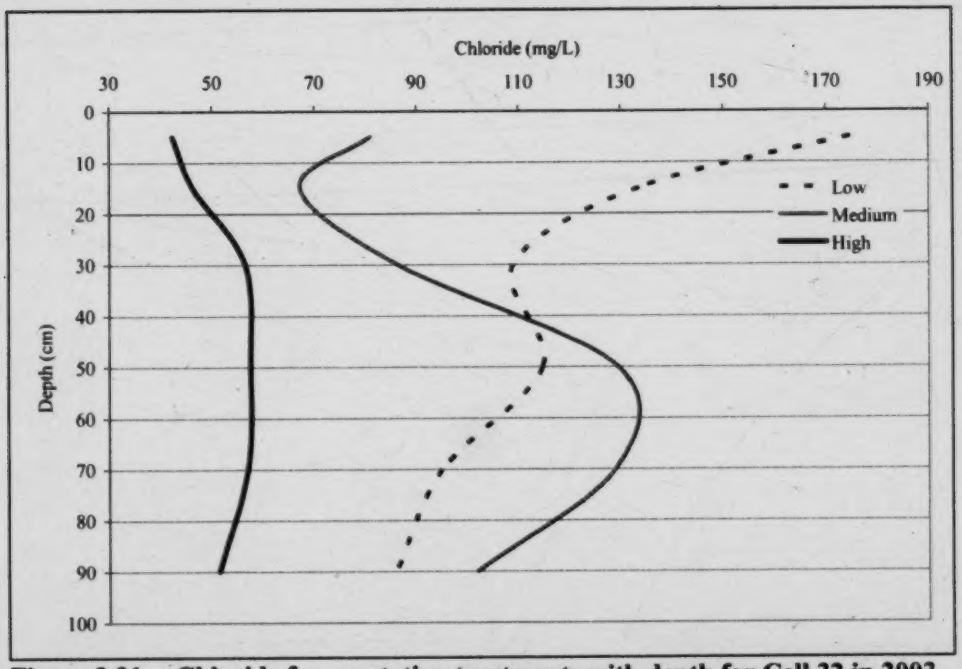

Figure 2.21 Chloride for vegetation treatments with depth for Cell 32 in 2003

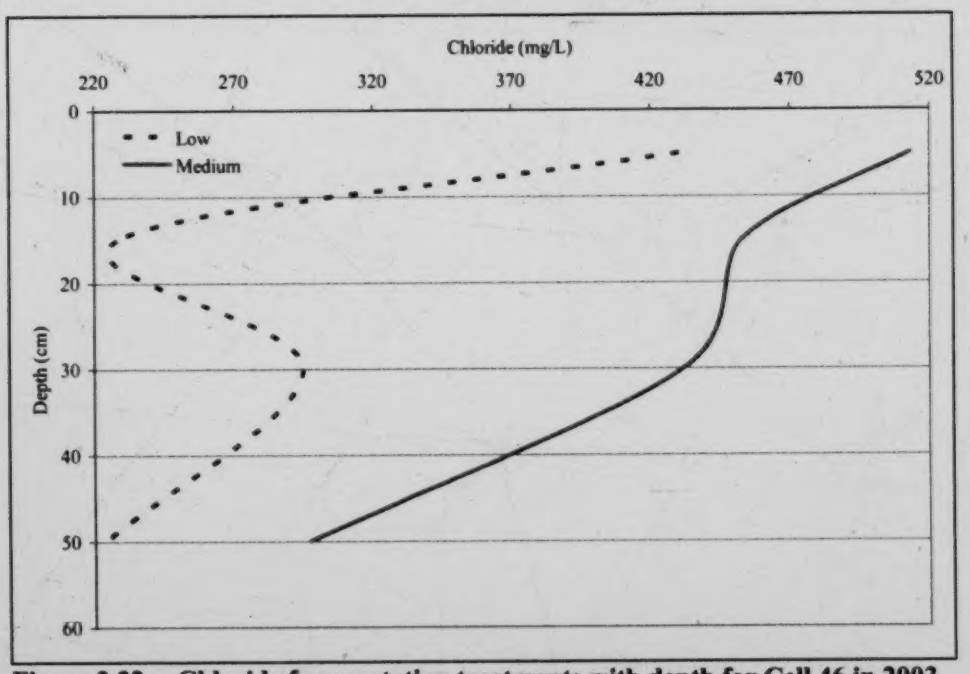

Figure 2.22 Chloride for vegetation treatments with depth for Cell 46 in 2003

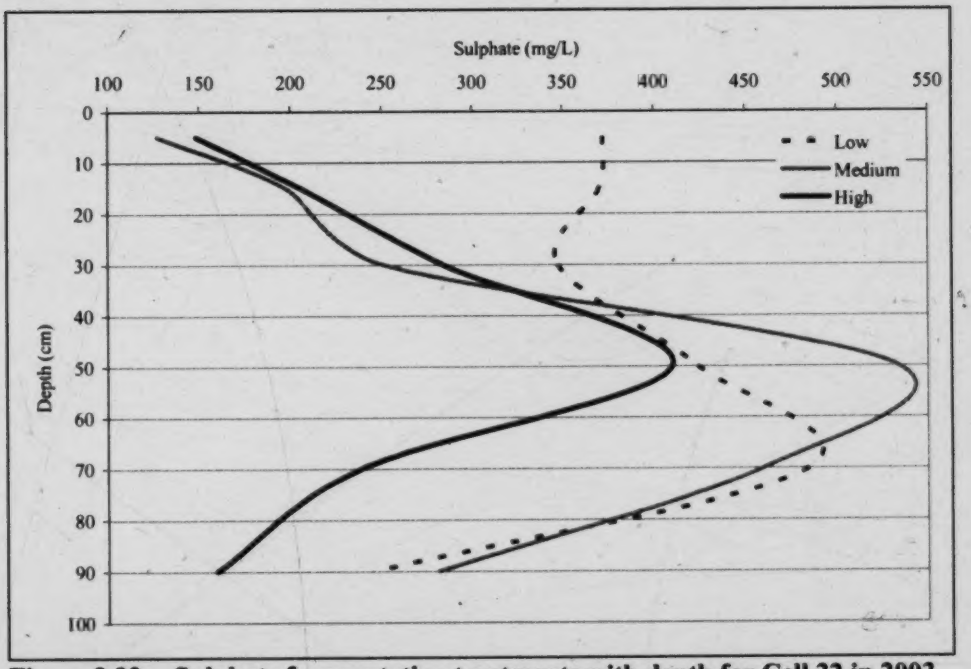

Figure 2.23 Sulphate for vegetation treatments with depth for Cell 32 in 2003

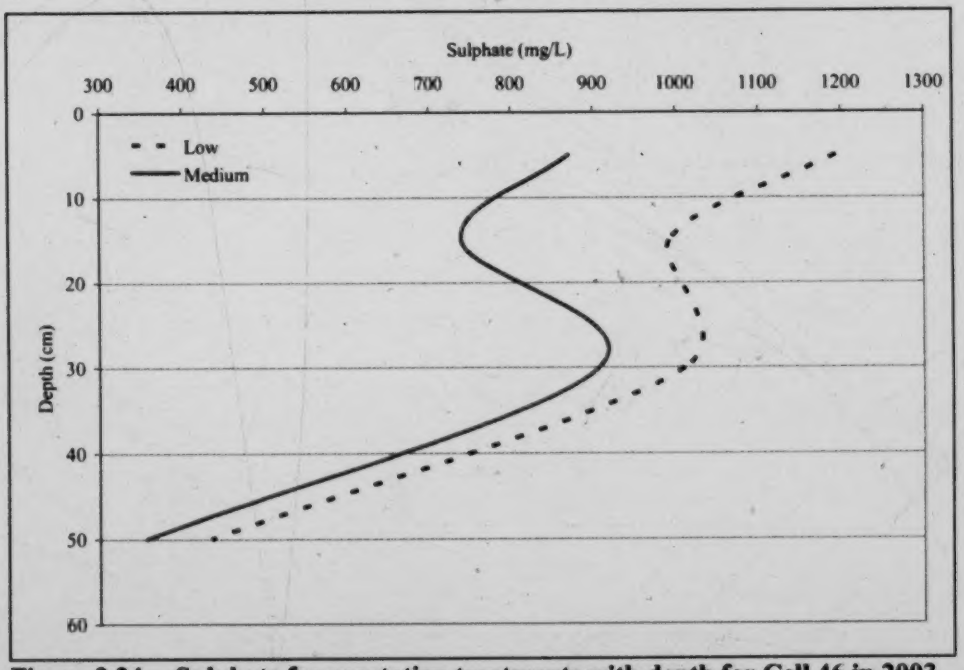

Figure 2.24 Sulphate for vegetation treatments with depth for Cell 46 in 2003

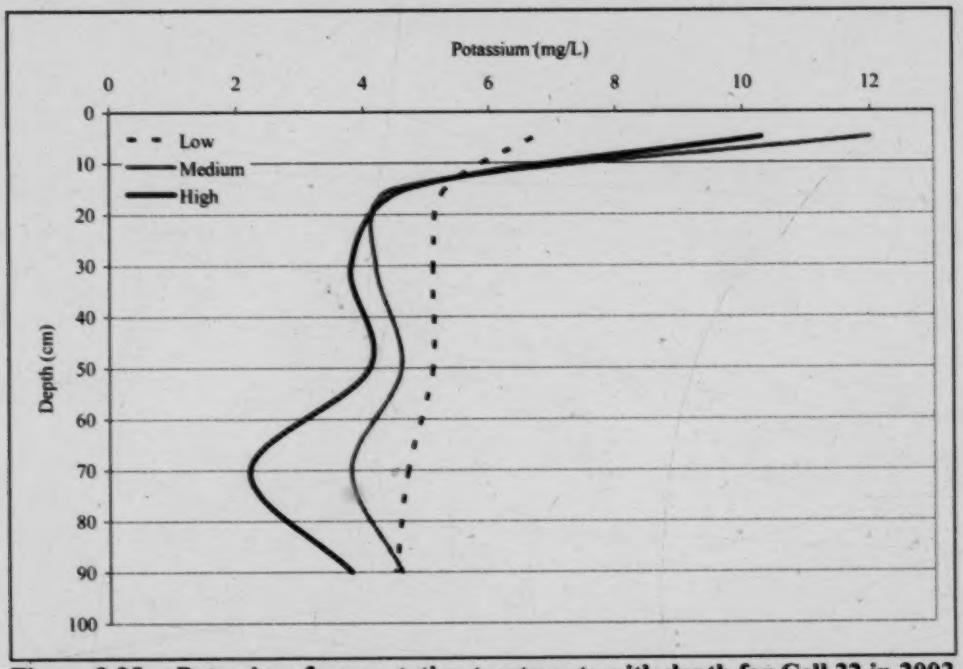

Figure 2.25 Potassium for vegetation treatments with depth for Cell 32 in 2003

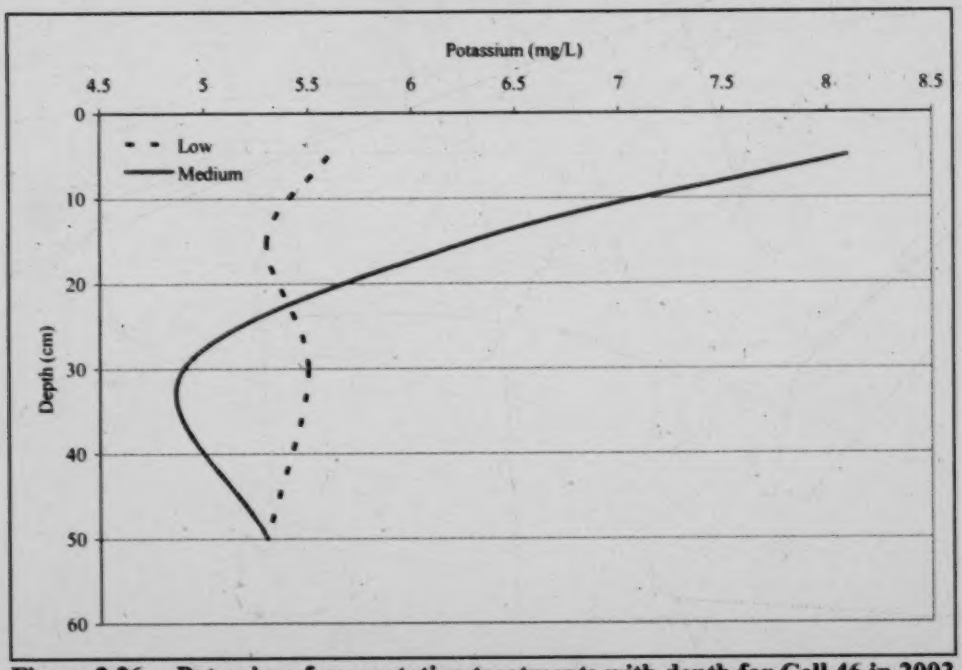

Figure 2.26 Potassium for vegetation treatments with depth for Cell 46 in 2003

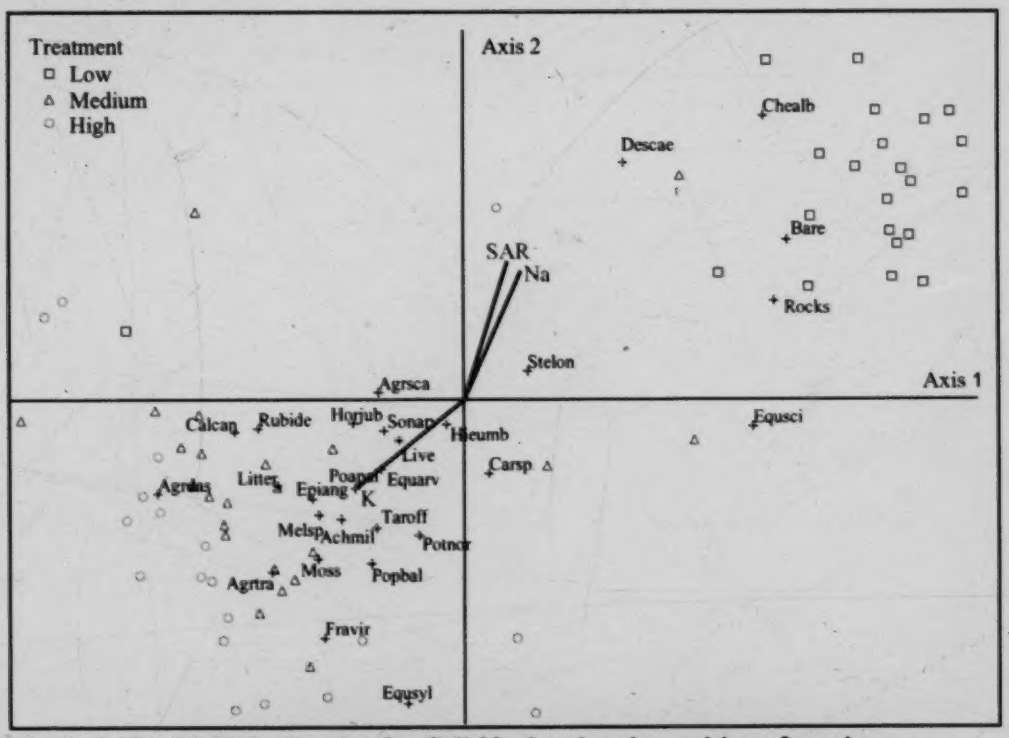

Figure 2.27 NMS Ordination for Cell 32, showing the position of species, vegetation treatments and vector plots with the relationship of soil variables (0 to 10 cm depth interval) within the ordination axes.

Species codes are as follows: Achmil, *Achillea millefolium*; Agrdas, *Agropyron dasystachyum*; Agrtra, *Agropyron trachycaulum*; Agrsca, *Agrostis scabra*; Calcan, *Calamagrostis canadensis*; Carsp., *Carex* spp.; Chealb, *Chenopodium album*; Descae, *Deschampsia caespitosa*; Epiang, *Epilobium angustifolium*; Equarv, *Equisetum arvense*; Equsci, *Equisetum sciropides*; Equsyl, *Equisetum sylvaticum*; Fravir, *Fragaria virginiana*; Hieumb, *Hieracium umbellatum*; Horjub, *Hordeum jubatum*; Melsp., *Melilotus* spp.; Poapal, *Poa palustris*; Popbal, *Populus balsamifera*; Potnor, *Potentilla norvegica*; Rubida, *Rubus idaeus*; Sonarv, *Sonchus arvensis*; Stelon, *Stellaria longifolia*; Taroff, *Taraxacum officinale*

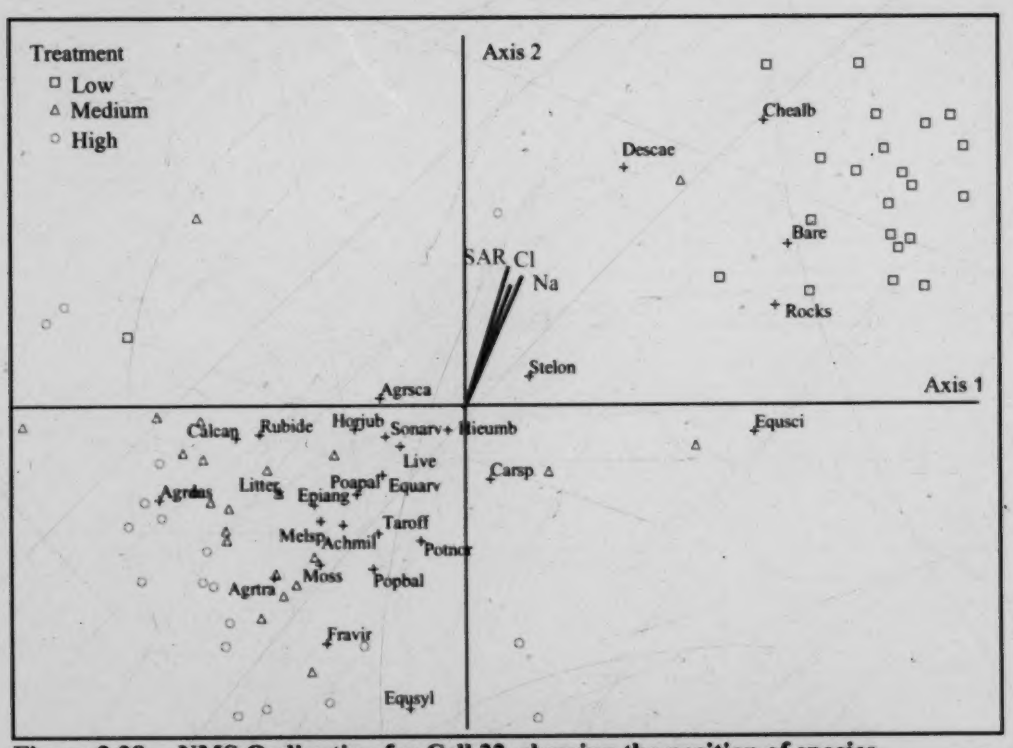

Figure 2.28 NMS Ordination for Cell 32, showing the position of species, vegetation treatments and vector plots with the relationship of soil variables (10 to 20 cm depth interval) within the ordination axes

Species codes are as follows: Achmil, *Achillea millefolium*; Agrdas, *Agropyron dasystachyum*; Agrtra, *Agropyron trachycaulum*; Agrsca, *Agrostis scabra*; Calcan, *Calamagrostis canadensis*; Carsp., *Carex* spp.; Chealb, *Chenopodium album*; Descae, *Deschampsia caespitosa*; Epiang, *Epilobium angustifolium*; Equarv, *Equisetum arvense*; Equsci, *Equisetum sciropides*; Equsyl, *Equisetum sylvaticum*; Fravir, *Fragaria virginiana*; Hieumb, *Hieracium umbellatum*; Horjub, *Hordeum jubatum*; Melsp., *Melilotus* spp.; Poapal, *Poa palustris*; Popbal, *Populus balsamifera*; Potnor, *Potentilla norvegica*; Rubida, *Rubus idaeus*; Sonarv, *Sonchus arvensis*; Stelon, *Stellaria longifolia*; Taroff, *Taraxacum officinale*

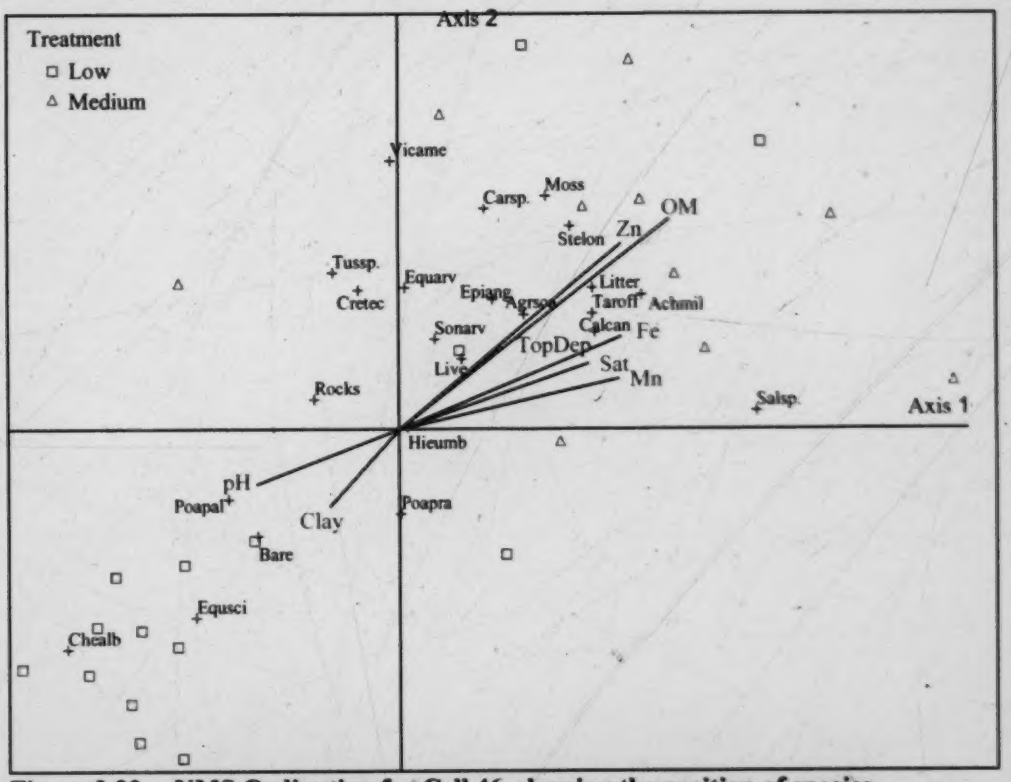

Figure 2.29 NMS Ordination for Cell 46, showing the position of species, vegetation treatments and vector plots with the relationship of soil variables (0 to 10 cm depth interval) within the ordination axes

Species codes are as follows: Achmil, *Achillea millefolium*; Agrsca, *Agrostis scabra*; Calcan, *Calamagrostis canadensis*; Carsp., *Carex* spp.; Chealb, *Chenopodium album*; Cretec, *Crepis tectorum*; Epiang, *Epilobium angustifolium*; Equarv, *Equisetum arvense*; Equsci, *Equisetum sciropides*; Hieumb, *Hieracium umbellatum*; Poapal, *Poa palustris*; Poapra, *Poa pratensis*; Salsp., *Salix* spp.; Sonarv, *Sonchus arvensis*; Stelon, *Stellaria longifolia*; Taroff, *Taraxacum officinale*; *Tussp.*, *Tussilago* spp.; Vicame, *Vicia americana*

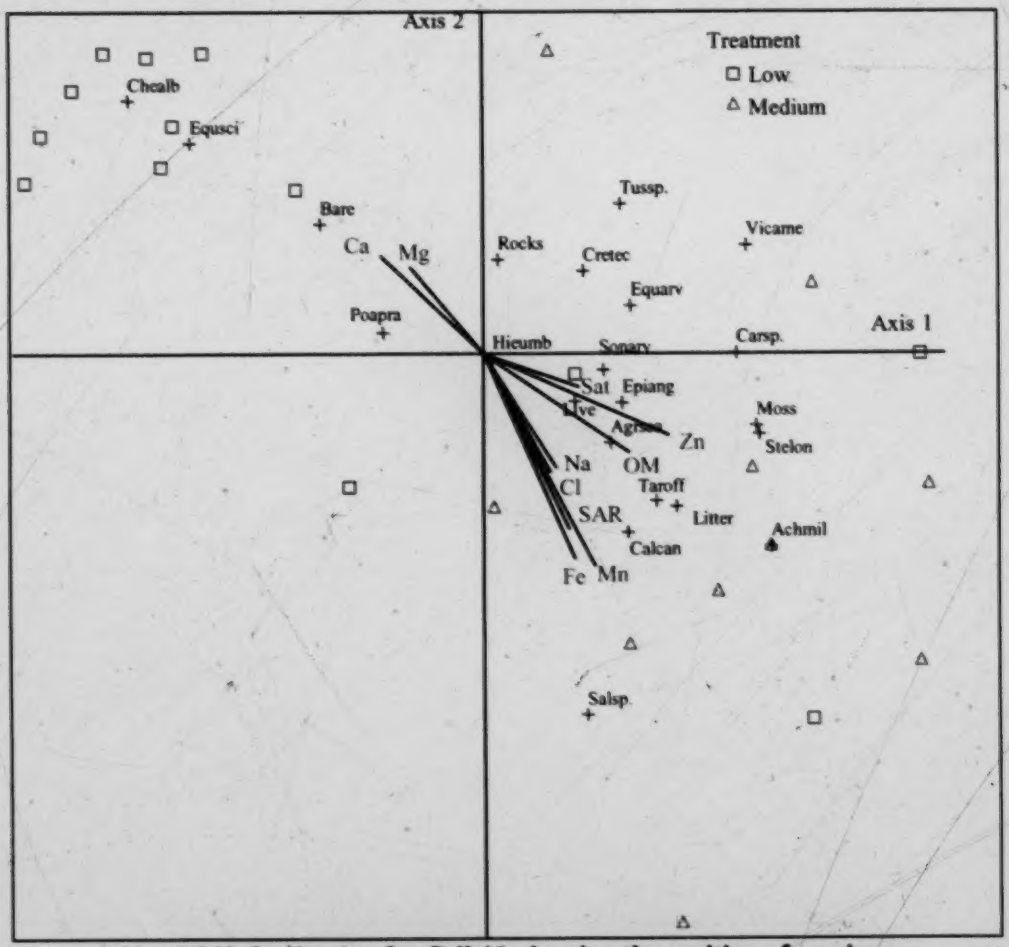

Figure 2.30 NMS Ordination for Cell 46, showing the position of species, vegetation treatments and vector plots with the relationship of soil variables (10 to 20 cm depth interval) within the ordination axes

Species codes are as follows: Achmil, *Achillea millefolium*; Agrsca, *Agrostis scabra*; Calcan, *Calamagrostis canadensis*; Carsp., *Carex* spp.; Chealb, *Chenopodium album*; Cretec, *Crepis tectorum*; Epiang, *Epilobium angustifolium*; Equarv, *Equisetum arvense*; Equsci, *Equisetum sciropides*; Hieumb, *Hieracium umbellatum*; Poapra, *Poa pratensis*; Salsp., *Salix* spp.; Sonarv, *Sonchus arvensis*; Stelon, *Stellaria longifolia*; Taroff, *Taraxacum officinale*; *Tussp.*, *Tussilago* spp.; Vicame, *Vicia americana*

Table 2.1 Long term climate normals (1971 to 2000) for Fort McMurray (Environment Canada 2003)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Year
Mean Temperature (°C)	-18.8	-13.7	-6.5	3.4	10.4	14.7	16.8	15.3	9.4	2.8	-8.5	-16.5	0.7
Mean Maximum Temperature (°C)	-13.6	-7.6	0.3	10.0	17.4	21.4	23.2	21.9	15.4	7.8	-4.2	-11.6	6.7
Mean Minimum Temperature (°C)	-24.0	-19.8	-13.2	-3.3	3.3	7.9	10.2	8.6	3.3	-2.2	-12.8	-21.4	-5.3
Mean Rainfall (mm)	0.5	0.8	1.6	9.3	34.2	74.8	81.3	72.6	45.0	18.8	2.4	1.1	342.2
Mean Snowfall (cm)	27.0	20.6	20.4	14.5	2.9	0.0	0.0	0.0	2.4	13.1	29.0	25.9	155.8
Total Precipitation (mm)	19.3	15.0	16.1	21.7	36.9	74.8	81.3	72.7	46.8	29.6	22.2	19.3	455.5

Table 2.2 Vegetation health rating classes

Rating Class	Description	Definition
1	Healthy	No signs of stress
2	Some signs of stress	Signs of chlorosis, leaf burning, browsing
3	Very poor health	Vegetation is dead or very near death

Table 2.3 Meteorological data for Cells 32 and 46 in 2003

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Year
Cell 32													
Mean Temperature (°C)	-15.9	-17.4	-10.1	3.9	10.1	14.4	17.9	16.5	9.7	5.3	-8.1	-10.5	1.3
Mean Maximum Temperature (°C)	-11.5	-12.0	-4.2	9.9	15.9	20.2	24.1	23.0	14.8	10.7	-3.8	-6.6	6.7
Mean Minimum Temperature (°C)	-20.7	-22.9	-15.9	-1.5	4.0	8.7	11.9	10.5	5.1	1.2	-12.2	-14.5	-3.8
Total Precipitation (mm)	0.0	0.0	26.9	13.2	34.8	62.7	70.9	21.3	99.6	42.4	0.0	0.0	371.8
Cell 46													
Mean Temperature (°C)	-16.8	-17.9	-10.7	3.3	9.6	14.2	17.8	16.1	9.3	4.5	-8.9	-11.1	0.8
Mean Maximum Temperature (°C)	-11.4	-12.5	-4.4	9.6	16.0	20.4	24.5	23.0	14.8	9.6	-4.4	-7.0	6.5
Mean Minimum Temperature (°C)	-22.9	-24.7	-17.8	-2.8	2.6	7.4	10.8	8.8	3.9	0.0	-13.6	-16.2	-5.4
Total Precipitation (mm)	0.0	0.0	26.9	13.2	30.0	57.2	77.5	25.4	104.9	44.4	0.0	0.0	379.5

Table 2.4 Meteorological data for Cells 32 and 46 in 2004

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Year
Cell 32													
Mean Temperature (°C)	-21.2	-10.2	-5.1	3.2	6.1	14.3	18.9	13.4	8.2	1.4			2.9
Mean Maximum Temperature (°C)	-17.8	-4.1	1.0	9.4	12.4	20.6	25.6	19.6	13.2	5.9			8.6
Mean Minimum Temperature (°C)	-25.0	-15.5	-11.6	-2.5	0.6	7.6	12.1	7.6	3.5	-2.6			-2.6
Total Precipitation (mm)	0.0	0.0	0.0	15.0	47.0	10.7	34.5	21.3	67.3	8.4			204.2
Cell 46													
Mean Temperature (°C)	-22.0	-10.8	-6.0	2.7	5.3	13.9	18.7	12.9	7.7	0.8			2.3
Mean Maximum Temperature (°C)	-18.3	-4.2	0.9	9.2	11.1	20.8	25.7	19.8	13.4	5.8			8.4
Mean Minimum Temperature (°C)	-26.3	-17.6	-14.0	-3.8	-1.1	5.0	10.7	5.5	2.1	-4.1			-4.3
Total Precipitation (mm)	6.1	2.8	0.0	10.7	45.7	13.0	39.4	27.4	68.1	7.9			221.0

Table 2.5 Meteorological data for the Fort McMurray Airport in 2003 and 2004 (Environment Canada 2004)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Year
2003													
Mean Temperature (°C)	-16.6	-18.6	-10.6	3.9	9.3	14.0	17.6	16.1	9.5	4.4	-9.4	-12.1	0.6
Mean Maximum Temperature (°C)	11.4	-12.0	-3.4	10.7	16.6	20.8	24.6	23.3	15.0	9.9	-4.0	-6.8	8.8
Mean Minimum Temperature (°C)	-21.8	-25.1	-17.8	-2.9	1.9	7.1	10.5	8.9	4.0	-1.0	-14.8	-17.3	-5.7
Mean Rainfall (mm)	0.2	0.0	1.9	8.4	39.9	84.5	69.9	48.7	86.2	35.4	0.0	0.0	375.1
Mean Snowfall (cm)	7.1	31.7	27.1	1.4	20.1	0.0	0.0	0.0	3.2	18.1	17.4	18.0	144.1
Total Precipitation (mm)	7.3	21.8	25.0	9.8	52.4	84.5	69.9	48.7	89.4	56.5	12.9	18.0	496.2
2004													
Mean Temperature (°C)	-21.4	-10.6	-6.5	3.0	5.7	13.3	18.0	12.7					1.8
Mean Maximum Temperature (°C)	-17.2	-3.6	1.3	9.8	12.2	21.4	25.8	20.1					8.7
Mean Minimum Temperature (°C)	-25.4	-17.5	-14.2	-3.9	-0.9	5.1	10.1	5.2					-5.2
Mean Rainfall (mm)	0.0	3.7	0.9	8.5	49.6	16.0	36.5	17.0					132.2
Mean Snowfall (cm)	48.7	20.4	20.3	14.5	5.0	0.0	0.0	0.0					108.9
Total Precipitation (mm)	38.3	16.9	15.0	23.0	54.6	16.0	36.5	17.0					217.3

Table 2.6 Vegetation properties by treatment for Cells 32 and Cell 46 in 2003

	Vegetation Treatment				
	Low	Medium	High	P Value	Average
Cell 32					
Canopy Cover (%)	8.9 (0.82) [c]	36.6 (1.85) [b]	76.8 (2.49) [a]	0.000	37.8
Bare Ground (%)	88.2 (5.11) [a]	9.2 (4.65) [b]	6.7 (3.43) [b]	0.000	37.8
Litter (%)	6.4 (3.74) [b]	74.0 (5.85) [a]	71.8 (5.54) [a]	0.000	48.2
Live (%)	1.5 (0.16) [c]	3.6 (0.27) [b]	5.6 (0.50) [a]	0.000	3.4
Moss (%)	3.2 (2.94) [b]	12.5 (3.25) [a]	16.5 (4.26) [a]	0.000	10.2
Rock (%)	0.9 (0.24) [a]	0.06 (0.04) [b]	0.18 (0.17) [b]	0.000	0.4
Health	1.1 (0.03) [a]	1.0 (0.00) [b]	1.0 (0.00) [b]	0.017	1.0
Cell 46					
Canopy Cover (%)	8.3 (1.53) [b]	34.6 (3.14) [a]		0.000	18.8
Bare Ground (%)	77.8 (9.068) [a]	20.7 (8.42) [b]		0.012	54.9
Litter (%)	18.0 (7.87) [b]	69.4 (9.16) [a]		0.000	38.6
Live (%)	2.1 (0.63) [b]	3.7 (0.46) [a]		0.035	2.7
Moss (%)	2.1 (1.59) [b]	5.8 (3.00) [a]		0.029	3.6
Rock (%)	0.2 (0.10) [a]	0.2 (0.16) [a]		0.976	0.2
Health	1.0 (0.02) [a]	1.0 (0.00) [a]		0.671	1.0

For Cell 32 n for Low = 26, Medium = 24 and High = 20
For Cell 46 n for Low = 15 and Medium = 10
Values reported as Mean (Standard Error)
Common letters in rows are not significantly different ($p <= 0.05$)

Table 2.7 Vegetation properties by bench for Cell 32 and Cell 46 in 2003

	Slope Position					
	Toe	Lower Forward	Lower Back	Upper Forward	Upper Back	P Value
Cell 32						
Canopy Cover (%)	19.5 (5.83) [a]	45.2 (6.93) [a]	38.4 (6.78) [a]	41.7 (8.59) [a]	38.2 (8.21) [a]	0.760
Bare Ground (%)	73.3 (12.29) [a]	34.0 (10.71) [ab]	32.1 (12.02) [ab]	25.7 (11.19) [b]	35.8 (11.66) [ab]	0.037
Litter (%)	23.1 (12.06) [a]	50.8 (10.45) [a]	55.2 (10.52) [a]	55.8 (10.48) [a]	47.8 (10.22) [a]	0.280
Live (%)	2.7 (0.41) [a]	3.8 (0.53) [a]	3.4 (0.62) [a]	3.4 (0.62) [a]	3.64 (0.69) [a]	0.860
Moss (%)	1.0 (0.51) [a]	11.1 (5.29) [a]	8.8 (3.23) [a]	14.59 (6.30) [a]	12.6 (3.67) [a]	0.345
Rock (%)	0.0 (0.00) [a]	0.4 (0.29) [a]	0.5 (0.24) [a]	0.6 (0.33) [a]	0.3 (0.12) [a]	0.088
Health	1.0 (0.00) [a]	1.1 (0.02) [a]	1.1 (0.05) [a]	1.0 (0.02) [a]	1.0 (0.0) [a]	0.224
Cell 46						
Canopy Cover (%)		22.2 (4.24) [a]		13.7 (3.85) [a]		0.793
Bare Ground (%)		49.0 (11.48) [a]		63.9 (12.53) [a]		0.854
Litter (%)		44.2 (10.79) [a]		30.1 (10.94) [a]		0.719
Live (%)		3.1 (0.64) [a]		2.2 (0.55) [a]		0.747
Moss (%)		4.0 (1.36) [a]		3.0 (2.75) [a]		0.711
Rock (%)		0.2 (0.11) [a]		0.2 (0.14) [a]		0.886
Health		1.0 (0.00) [a]		1.0 (0.03) [a]		0.327

For Cell 32 n for Toe = 10, Lower Forward = 15, Lower Back = 15, Upper Forward = 15 and Upper Back = 15;
For Cell 46 n for Lower Forward = 15 and Upper Forward = 10
Values reported as Mean (Standard Error)
Common letters in rows are not significantly different ($p <= 0.05$)

Table 2.8 **Soil textural classes (0 to 10 cm depth interval) and clay, silt and sand (%) for each vegetation treatment on Cells 32 and 46**

	Vegetation Treatment			
	Low	Medium	High	P Value
Cell 32				
Total Clay (%)	26.38 (3.36) [a]	29.44 (2.43) [a]	37.17 (2.91) [a]	0.124
Total Silt (%)	21.48 (2.49) [a]	25.79 (2.31) [a]	20.90 (0.97) [a]	0.232
Total Sand (%)	52.14 (4.98) [a]	44.77 (2.75) [a]	41.93 (3.54) [a]	0.551
Texture	sandy clay loam	clay loam	clay loam	
Cell 46				
Total Clay (%)	28.76 (3.13) [a]	21.74 (1.36) [a]		0.212
Total Silt (%)	38.41 (2.26) [a]	37.71 (1.36) [a]		0.916
Total Sand (%)	32.83 (2.80) [a]	40.55 (2.73) [a]		0.714
Texture	clay loam	loam		

For Cell 32 n for Low = 23, Medium = 15 and High = 15
For Cell 46 n for Low = 15 and Medium = 10
Values reported as Mean (Standard Error)
Common letters in rows are not signigicantly different ($p <= 0.05$)

Table 2.9 Soil properties by treatment (0 to 10 cm depth interval) for Cell 32 in 2003

	Low	Medium	High	P Value
Soil Depth (cm)	78 (2.64) [a]	82 (3.43) [a]	81 (2.74) [a]	0.399
pH	7.5 (0.11) [a]	7.1 (0.11) [b]	7.2 (0.07) [b]	0.011
Electrical conductivity (dS/m)	1.4 (0.29) [a]	1.0 (0.11) [a]	1.0 (0.12) [a]	0.220
Sodium adsorption ratio	4.3 (1.38) [a]	2.2 (0.89) [ab]	1.2 (0.68) [b]	0.026
Saturation (%)	51 (6.81) [a]	54 (5.64) [a]	48 (3.32) [a]	0.529
Na^+ (mg/L)	162 (47.79) [a]	72 (26.70) [ab]	45 (18.86) [b]	0.045
Mg^{2+} (mg/L)	33 (7.96) [a]	29 (2.60) [a]	37 (4.73) [a]	0.478
Ca^{2+} (mg/L)	131 (32.83) [a]	112 (12.82) [a]	133 (21.94) [a]	0.975
K^+ (mg/L)	7 (1.27) [b]	12 (1.40) [a]	10 (1.56) [a]	0.013
Cl^- (mg/L)	175 (71.16) [a]	81 (27.10) [a]	42 (9.97) [a]	0.827
SO_4^{2-} (mg/L)	372 (119.24) [a]	127 (29.66) [b]	148 (70.98) [b]	0.017
Organic carbon (%)	2.1 (0.53) [a]	3.1 (0.56) [a]	2.4 (0.22) [a]	0.106
Organic matter (%)	3.6 (0.92) [a]	5.3 (0.95) [a]	4.2 (0.38) [a]	0.138
Cu^{2+} (mg/kg)	0.92 (0.10) [a]	1.10 (0.09) [a]	1.16 (0.15) [a]	0.689
Fe^{2+} (mg/kg)	68 (29.26) [a]	81 (26.74) [a]	38 (3.59) [a]	0.196
Mn^{2+} (mg/kg)	3.80 (0.81) [a]	6.03 (1.41) [a]	4.70 (0.60) [a]	0.322
Zn^{2+} (mg/kg)	0.8 (0.17) [a]	1.0 (0.15) [a]	0.8 (0.11) [a]	0.515
$NO_3^- + NO_2^-$ (mg/L)	0.1 (0.05) [a]	0.1 (0.02) [a]	0.1 (0.06) [a]	0.254
PO_4^{3-} (mg/L)	0 (0.24) [a]	0 (0.10) [a]	0 (0.05) [a]	0.952

Values reported as Mean (Standard Error)
Common letters in rows are not significantly different at ($p \leq 0.05$)
Sample size for low = 23, medium = 23 and high = 20

Table 2.10 Soil properties by treatment (0 to 10 cm depth interval) for Cell 46 in 2003

	Low	Medium	P Value
Soil Depth (cm)	32 (3.49) [b]	41 (3.84) [a]	0.032
pH	6.4 (0.31) [a]	5.7 (0.24) [b]	0.044
Electrical conductivity (dS/m	3.2 (0.73) [a]	3.1 (0.61) [a]	0.338
Sodium adsorption ratio	4.9 (1.32) [a]	9.2 (2.67) [a]	0.132
Saturation (%)	102 (14.48) [b]	153 (20.71) [a]	0.021
Na^+ (mg/L)	403 (139.24) [a]	498 (121.59) [a]	0.287
Mg^{2+} (mg/L)	81 (18.14) [a]	52 (9.29) [a]	0.957
Ca^{2+} (mg/L)	300 (60.18) [a]	180 (43.92) [a]	0.607
K^+ (mg/L)	6 (0.96) [b]	8 (1.41) [a]	0.015
Cl^- (mg/L)	431 (177.89) [a]	513 (128.11) [a]	0.117
SO_4^{2-} (mg/L)	1195 (245.61) [a]	871 (211.19) [a]	0.941
Organic carbon (%)	4.9 (1.01) [b]	9.4 (0.91) [a]	0.014
Organic matter (%)	11.9 (2.38) [b]	21.6 (1.95) [a]	0.008
Cu^{2+} (mg/kg)	0.81 (0.06) [a]	0.76 (0.06) [a]	0.497
Fe^{2+} (mg/kg)	162 (50.92) [b]	378 (61.67) [a]	0.002
Mn^{2+} (mg/kg)	9.87 (2.68) [b]	20.95 (4.13) [a]	0.010
Zn^{2+} (mg/kg)	1.8 (0.38) [b]	3.6 (0.42) [a]	0.009
$NO_3^- + NO_2^-$ (mg/L)	0.1 (0.04) [a]	0.0 (0.03) [a]	0.859
PO_4^{3-} (mg/L)	0 (0.00) [a]	0 (0.30) [a]	0.357

Values reported as Mean (Standard Error)
Common letters in rows are not significantly different at ($p \leq 0.05$)
Sample size for low = 15 and medium = 10

Table 2.11 Soil properties by treatment (10 to 20 cm depth interval) for Cell 32 in 2003

	Low	Medium	High	P Value
pH	7.6 (0.09) [a]	7.3 (0.14) [a]	7.3 (0.05) [a]	0.041
Electrical conductivity (dS/m)	1.8 (0.22) [a]	0.9 (0.11) [a]	0.9 (0.18) [a]	0.151
Sodium adsorption ratio	4.1 (1.22) [a]	2.5 (0.84) [a]	2.0 (1.21) [a]	0.174
Na^+ (mg/L)	151 (39.09) [a]	84 (22.92) [a]	72 (34.62) [a]	0.391
Mg^{2+} (mg/L)	30 (6.15) [a]	22 (2.58) [a]	31 (5.45) [a]	0.164
Ca^{2+} (mg/L)	114 (27.73) [a]	91 (14.27) [a]	109 (27.38) [a]	0.722
K^+ (mg/L)	5 (0.84) [a]	4 (0.57) [a]	5 (1.13) [a]	0.343
Cl^- (mg/L)	134 (47.51) [a]	67 (19.85) [a]	46 (25.56) [a]	0.873
SO_4^{2-} (mg/L)	371 (115.44) [a]	198 (45.85) [a]	206 (102.22) [a]	0.106
Saturation (%)	41 (1.81) [b]	54 (5.55) [a]	51 (2.54) [a]	0.444
Organic carbon (%)	1.4 (0.16) [b]	2.9 (0.55) [a]	2.8 (0.33) [a]	0.040
Organic matter (%)	2.4 (0.27) [a]	5.0 (0.94) [a]	4.8 (0.57) [a]	0.054
Cu^{2+} (mg/kg)	0.93 (0.14) [a]	1.14 (0.07) [a]	1.26 (0.10) [a]	0.481
Fe^{2+} (mg/kg)	30 (4.22) [b]	69 (23.07) [a]	51 (4.5) [a]	0.005
Mn^{2+} (mg/kg)	3.04 (0.38) [a]	4.34 (0.41) [a]	4.65 (0.86) [a]	0.342
Zn^{2+} (mg/kg)	0.6 (0.14) [a]	0.7 (0.13) [a]	0.8 (0.12) [a]	0.425
$NO_3^- + NO_2^-$ (mg/L)	0.1 (0.03) [a]	0.1 (0.02) [a]	0.1 (0.03) [a]	0.545
PO_4^{3-} (mg/L)	0 (0.06) [a]	0 (0.00) [a]	0 (0.00) [a]	0.331

Values reported as Mean (Standard Error)
Common letters in rows are not significantly different at ($p \leq 0.05$)
Sample size for low = 24, medium = 23 and high = 19

Table 2.12 Soil properties by treatment (10 to 20 cm depth interval) for Cell 46 in 2003

	Low	Medium	P Value
pH	6.5 (0.34) [a]	6.1 (0.21) [a]	0.085
Electrical conductivity (dS/m)	2.4 (0.32) [a]	2.8 (0.42) [a]	0.301
Sodium adsorption ratio	4.6 (1.16) [b]	11.6 (2.65) [a]	0.029
Na^+ (mg/L)	257 (55.87) [a]	496 (95.15) [a]	0.102
Mg^{2+} (mg/L)	63 (11.28) [a]	38 (6.81) [a]	0.312
Ca^{2+} (mg/L)	251 (50.15) [a]	124 (22.33) [a]	0.142
K^+ (mg/L)	5 (0.80) [a]	6 (2.11) [a]	0.693
Cl^- (mg/L)	228 (66.18) [a]	453 (100.93) [a]	0.067
SO_4^{2-} (mg/L)	993 (158.93) [a]	740 (130.13) [a]	0.574
Saturation (%)	125 (45.81) [a]	119 (12.51) [a]	0.137
Organic carbon (%)	4.8 (1.12) [b]	9.0 (0.72) [a]	0.013
Organic matter (%)	13.1 (4.09) [a]	17.1 (2.58) [a]	0.218
Cu^{2+} (mg/kg)	0.97 (0.08) [a]	0.77 (0.06) [a]	0.132
Fe^{2+} (mg/kg)	152.8 (45.73) [b]	331.6 (53.25) [a]	0.006
Mn^{2+} (mg/kg)	9.16 (3.71) [b]	21.34 (6.14) [a]	0.008
Zn^{2+} (mg/kg)	1.9 (0.78) [a]	2.8 (0.25) [a]	0.210
$NO_3^- + NO_2^-$ (mg/L)	0.1 (0.03) [a]	0.1 (0.03) [a]	0.458
PO_4^{3-} (mg/L)	0 (0.27) [a]	0 (0.00) [a]	0.482

Values reported as Mean (Standard Error)
Common letters in rows are not significantly different at ($p \leq 0.05$)
Sample size for low = 13 and medium = 10

Table 2.13 Soil properties by treatment (20 to 40 cm depth interval) for Cells 32 and 46 in 2003

	Low	Medium	High	P Value
Cell 32				
pH	7.8 (0.10) [a]	7.4 (0.13) [a]	7.3 (0.12) [a]	0.056
Electrical conductivity (dS/m)	1.2 (0.17) [a]	1.0 (0.10) [a]	1.0 (0.20) [a]	0.746
Sodium adsorption ratio	5.0 (1.49) [a]	3.7 (1.07) [a]	2.5 (1.24) [a]	0.415
Na^+ (mg/L)	145 (31.28) [a]	114 (21.74) [a]	95 (35.09) [a]	0.644
Mg^{2+} (mg/L)	25 (6.07) [a]	25 (2.46) [a]	32 (6.29) [a]	0.342
Ca^{2+} (mg/L)	96 (22.97) [a]	91 (13.26) [a]	109 (25.00) [a]	0.768
K^+ (mg/L)	5 (0.81) [a]	4 (0.51) [a]	4 (0.86) [a]	0.068
Cl^- (mg/L)	109 (37.81) [a]	86 (24.23) [a]	57 (30.66) [a]	0.780
SO_4^{2-} (mg/L)	348 (98.49) [a]	252 (38.04) [a]	284 (106.99) [a]	0.492
Saturation (%)	42 (1.94) [a]	70 (17.19) [a]	58 (5.02) [a]	0.332
$NO_3^- + NO_2^-$ (mg/L)	0.2 (0.07) [a]	0.1 (0.03) [a]	0.1 (0.02) [a]	0.100
PO_4^{3-} (mg/L)	0 (0.00) [a]	0 (0.10) [a]	0 (0.00) [a]	0.058
Cell 46				
pH	7.1 (0.17) [a]	6.8 (0.19) [b]		0.049
Electrical conductivity (dS/m)	2.7 (0.28) [a]	3.2 (0.26) [a]		0.155
Sodium adsorption ratio	6.0 (1.50) [b]	13.7 (2.31) [a]		0.017
Na^+ (mg/L)	333 (63.51) [b]	566 (71.88) [a]		0.041
Mg^{2+} (mg/L)	65 (11.23) [a]	46 (14.86) [a]		0.183
Ca^{2+} (mg/L)	254 (56.22) [a]	150 (56.49) [a]		0.062
K^+ (mg/L)	6 (0.92) [a]	5 (0.42) [a]		0.986
Cl^- (mg/L)	295 (77.95) [a]	432 (89.51) [a]		0.133
SO_4^{2-} (mg/L)	1011 (178.54) [a]	907 (186.24) [a]		0.641
Saturation (%)	85 (17.99) [b]	111 (22.15) [a]		0.023
$NO_3^- + NO_2^-$ (mg/L)	0.1 (0.05) [a]	0.0 (0.03) [a]		0.929
PO_4^{3-} (mg/L)	0 (0.09) [a]	0 (0.00) [a]		0.604

Values reported as Mean (Standard Error)
Common letters in rows are not significantly different at ($p \leq 0.05$)
For Cell 32 n for low = 24, medium = 23 and high = 20
For Cell 46 n for low = 11 and medium = 9

Table 2.14 Soil properties by treatment (40 to 60 and 60 to 80 cm depth intervals) for Cell 32 in 2003

	Low	Medium	High	P Value
40 to 60 cm				
pH	7.9 (0.11) [a]	7.4 (0.10) [b]	7.4 (0.11) [b]	0.007
Electrical conductivity (dS/m)	1.3 (0.19) [a]	1.6 (0.20) [a]	1.2 (0.26) [a]	0.327
Sodium adsorption ratio	7.1 (1.80) [a]	4.9 (1.14) [a]	3.8 (1.96) [a]	0.583
Na^+ (mg/L)	190 (36.00) [a]	196 (37.01) [a]	130 (44.75) [a]	0.270
Mg^{2+} (mg/L)	30 (10.68) [a]	35 (6.18) [a]	333 (7.00) [a]	0.393
Ca^{2+} (mg/L)	89 (24.71) [a]	138 (27.19) [a]	120 (28) [a]	0.347
K^+ (mg/L)	5 (0.98) [a]	5 (0.51) [a]	4 (1.18) [a]	0.086
Cl^- (mg/L)	115 (32.57) [a]	129 (36.71) [a]	57 (27.04) [a]	0.544
SO_4^{2-} (mg/L)	424 (120.26) [a]	533 (107.43) [a]	410 (144.53) [a]	0.176
Saturation (%)	41 (1.80) [a]	67 (14.01) [a]	49 (2.09) [a]	0.152
$NO_3^- + NO_2^-$ (mg/L)	0.5 (0.15) [a]	0.1 (0.03) [b]	0.2 (0.08) [ab]	0.012
PO_4^{3-} (mg/L)	0 (0.00) [a]	0 (0.10) [a]	0 (0.00) [a]	0.141
60 to 80 cm				
pH	7.8 (0.13) [a]	7.5 (0.13) [a]	7.3 (0.13) [a]	0.712
Electrical conductivity (dS/m)	1.4 (0.21) [a]	1.4 (0.13) [a]	1.2 (0.15) [a]	0.165
Sodium adsorption ratio	6.2 (1.54) [a]	5.9 (1.36) [a]	2.9 (0.83) [a]	0.317
Na^+ (mg/L)	180 (32.34) [a]	193 (29.99) [a]	121 (28.03) [a]	0.189
Mg^{2+} (mg/L)	33 (13.63) [a]	28 (4.01) [a]	33 (4.96) [a]	0.891
Ca^{2+} (mg/L)	114 (39.21) [a]	105 (21.06) [a]	106 (17.31) [a]	0.984
K^+ (mg/L)	5 (0.99) [a]	4 (0.42) [a]	3 (0.47) [b]	0.018
Cl^- (mg/L)	95 (29.79) [a]	90 (28.57) [a]	44 (15.09) [a]	0.592
SO_4^{2-} (mg/L)	517 (163.5) [a]	456 (77.52) [a]	395 (73.37) [a]	0.467
Saturation (%)	40 (2.75) [a]	85 (34.48) [a]	48 (2.57) [a]	0.137
$NO_3^- + NO_2^-$ (mg/L)	0.4 (0.07) [a]	0.2 (0.04) [b]	0.1 (0.04) [b]	0.006
PO_4^{3-} (mg/L)	0 (0.00) [a]	0 (0.12) [a]	0 (0.00) [a]	0.550

Values reported as Mean (Standard Error)
Common letters in rows are not significantly different at ($p \leq 0.05$)
For 40 to 60 cm interval n for low = 23, medium = 22 and high = 19
For 60 to 80 cm interval n for low = 18, medium = 20 and high = 17

Table 2.15 Soil properties by treatment for the tailings sand for Cell 32 and Cell 46 in 2003

	Low	Medium	High	P Value
Cell 32				
pH	7.8 (0.08) [a]	7.9 (0.10) [a]	7.6 (0.09) [a]	0.158
Electrical conductivity (dS/m)	1.0 (0.14) [a]	1.2 (0.13) [a]	0.7 (0.10) [a]	0.636
Sodium adsorption ratio	5.6 (2.01) [a]	8.6 (1.74) [a]	4.0 (1.01) [a]	0.525
Na^+ (mg/L)	125 (30.24) [a]	204 (34.04) [a]	102 (25.10) [b]	0.038
Mg^{2+} (mg/L)	20 (4.28) [a]	17 (2.79) [a]	15 (1.28) [a]	0.908
Ca^{2+} (mg/L)	59 (14.95) [a]	55 (13.94) [a]	38 (3.48) [a]	0.569
K^+ (mg/L)	5 (0.52) [a]	5 (0.40) [a]	4 (0.35) [b]	0.046
Cl^- (mg/L)	86 (26.19) [a]	102 (28.4) [a]	51 (16.39) [a]	0.637
SO_4^{2-} (mg/L)	244 (65.50) [a]	281 (47.02) [a]	159 (25.69) [a]	0.067
Saturation (%)	32 (1.54) [a]	34 (1.76) [a]	32 (0.95) [a]	0.169
$NO_3^- + NO_2^-$ (mg/L)	0.3 (0.08) [a]	0.3 (0.09) [a]	0.3 (0.09) [a]	0.884
PO_4^{3-} (mg/L)	0 (0.05) [a]	0 (0.04) [a]	0 (0.10) [a]	0.931
Cell 46				
pH	7.7 (0.10) [a]	7.7 (0.17) [a]		0.726
Electrical conductivity (dS/m)	1.7 (0.24) [a]	2.2 (0.30) [a]		0.102
Sodium adsorption ratio	7.4 (1.76) [b]	14.8 (30.00) [a]		0.038
Na^+ (mg/L)	260 (55.84) [a]	395 (57.07) [a]		0.120
Mg^{2+} (mg/L)	25 (2.61) [a]	30 (16.68) [a]		0.213
Ca^{2+} (mg/L)	79 (13.89) [a]	84 (48.4) [a]		0.120
K^+ (mg/L)	5 (0.54) [a]	5 (0.86) [a]		0.751
Cl^- (mg/L)	224 (56.28) [a]	297 (63.64) [a]		0.238
SO_4^{2-} (mg/L)	434 (52.27) [a]	357 (223.27) [a]		0.794
Saturation (%)	35 (2.32) [a]	35 (2.94) [a]		0.507
$NO_3^- + NO_2^-$ (mg/L)	0.1 (0.04) [a]	0.1 (0.04) [a]		0.752
PO_4^{3-} (mg/L)	0 (0.00) [a]	0 (0.00) [a]		

Values reported as Mean (Standard Error)
Common letters in rows are not significantly different at ($p \leq 0.05$)
For Cell 32 n for low = 26, medium = 24 and high = 20
For Cell 46 n for low = 15 and medium = 10

Table 2.16 Soil pH suitability classes with depth, for Cells 32 and 46 in 2003

		Number of Vegetation Plots Per Treatment				
		Cell 32			Cell 46	
	Guideline Value	Low	Medium	High	Low	Medium
0 to 10 cm						
Good	5.0 to 6.5	1	2	1	3	8
Fair	4.0 to 5.0 or	0	0	0	4	1
	6.5 to 7.5	9	19	17	8	1
Poor	3.5 to 4.0 or	0	0	0	0	0
	7.5 to 9.0	13	2	2	1	0
Unsuitable	<3.5 and >9.0	0	0	0	0	0
10 to 20 cm						
Good	5.0 to 6.5	0	1	0	1	6
Fair	4.0 to 5.0 or	0	1	0	3	1
	6.5 to 7.5	13	14	18	8	3
Poor	3.5 to 4.0 or	0	0	0	0	0
	7.5 to 9.0	11	7	1	1	0
Unsuitable	<3.5 and >9.0	0	0	0	0	0
20 to 40 cm						
Good	5.0 to 6.5	0	0	2	3	3
Fair	4.0 to 5.0 or	0	1	0	0	0
	6.5 to 7.5	6	13	14	7	5
Poor	3.5 to 4.0 or	0	0	0	0	0
	7.5 to 9.0	18	9	4	1	1
Unsuitable	<3.5 and >9.0	0	0	0	0	0

Table 2.17 Soil electrical conductivity suitability classes with depth, for Cell 32 and Cell 46 in 2003

		Number of Vegetation Plots Per Treatment				
		Cell 32			Cell 46	
	Guideline Value	Low	Medium	High	Low	Medium
0 to 10 cm						
Good	<2	18	22	19	7	4
Fair	2 to 4	3	1	1	3	1
Poor	4 to 8	2	0	0	4	5
Unsuitable	>8	0	0	0	1	0
10 to 20 cm						
Good	<2	17	21	17	4	3
Fair	2 to 4	7	2	2	7	5
Poor	4 to 8	0	0	0	2	2
Unsuitable	>8	0	0	0	0	0
20 to 40 cm						
Good	<2	19	21	18	2	0
Fair	2 to 4	5	2	2	8	7
Poor	4 to 8	0	0	0	1	2
Unsuitable	>8	0	0	0	0	0
40 to 60 cm						
Good	<3	22	20	18		
Fair	3 to 5	1	2	1		
Poor	5 to 8	0	0	0		
Unsuitable	>8	0	0	0		
60 to 80 cm						
Good	<3	17	20	17		
Fair	3 to 5	1	0	0		
Poor	5 to 8	0	0	0		
Unsuitable	>8	0	0	0		
Talings Sand						
Good	<3	26	24	20	13	9
Fair	3 to 5				2	1
Poor	5 to 8					
Unsuitable	>8					

Table 2.18 Soil sodium adsorption ratio suitability classes, with depth, for Cells 32 and 46 in 2003

		Number of Vegetation Plots Per Treatment				
		Cell 32			Cell 46	
	Guideline Value	Low	Medium	High	Low	Medium
0 to 10 cm						
Good	< 4	17	21	19	10	3
Fair	4 to 8	3	0	0	2	3
Poor	8 to 12	0	0	0	1	2
Unsuitable	> 12	3	2	1	2	2
10 to 20 cm						
Good	< 4	18	20	18	8	2
Fair	4 to 8	3	1	0	3	3
Poor	8 to 12	0	0	0	0	0
Unsuitable	>12	3	2	1	2	5
20 to 40 cm						
Good	< 4	16	18	19	5	1
Fair	4 to 8	4	2	0	4	0
Poor	8 to 12	1	0	0	0	1
Unsuitable	>12	3	3	1	2	7
40 to 60 cm						
Good	< 4	14	14	17		
Fair	4 to 8	2	3	1		
Poor	8 to 12	2	4	0		
Unsuitable	>12	5	1	1		
60 to 80 cm						
Good	< 4	11	11	15		
Fair	4 to 8	2	5	0		
Poor	8 to 12	0	0	1		
Unsuitable	>12	5	4	1		
Tailings Sand						
Good	< 4	19	10	13	8	2
Fair	4 to 8	3	4	5	1	1
Poor	8 to 12	4	10	2	6	7
Unsuitable	>12	0	0	0	0	0

Table 2.19 Deficiency classes and ranges for extractable micronutrients in soil

	Concentration (mg/kg)		
Micronutrient	Deficient	Marginal	Adequate
Copper			
Soil with <7% organic matter	0.0 to 0.4	0.5 to 0.6	> 0.6
Soil with >7% organic matter	0.0 to 0.6	0.7 to 1.0	>1.0
Iron	0.0 to 2.0	2.0 to 4.5	> 4.5
Manganese	0.0 to 1.0	~	> 1.0
Zinc	0.0 to 0.5	0.6 to 1.0	>1.0

Adapted from McKenzie 1992 and Solberg et al. 1999

Table 2.20 Classification of extractable micronutrients deficiencies with depth for Cell 32 in 2003

	Number of Sites Within Each Vegetation Class								
	Low			Medium			High		
	Deficient	Marginal	Adequate	Deficient	Marginal	Adequate	Deficient	Marginal	Adequate
0 to 10 cm									
Copper									
Soil with <7% organic matter	5	1	15	0	3	17	2	0	17
Soil with >7% organic matter	1	0	1	1	0	2	0	0	1
Iron	0	0	23	0	0	23	0	0	20
Manganese	2	~	21	0	~	23	0	~	20
Zinc	16	3	4	7	10	6	7	10	3
10 to 20 cm									
Copper									
Soil with <7% organic matter	8	0	16	1	0	20	1	0	15
Soil with >7% organic matter	0	0	0	1	0	1	0	1	2
Iron	0	0	24	0	0	23	0	0	19
Manganese	1	~	23	1	~	22	0	~	19
Zinc	15	1	8	14	6	3	10	5	4

Adapted from McKenzie 1992 and Solberg et al. 1999

Table 2.21 Classification of extractable micronutrients deficiencies with depth for Cell 46 in 2003

	Number of Sites Within Each Vegetation Class					
	Low			Medium		
	Deficient	Marginal	Adequate	Deficient	Marginal	Adequate
0 to 10 cm						
Copper						
Soil with <7% organic matter	0	2	5	0	0	0
Soil with >7% organic matter	2	5	2	3	5	2
Iron	0	0	15	0	0	10
Manganese	0	~	15	0	~	10
Zinc	5	2	8	0	0	10
10 to 20 cm						
Copper						
Soil with <7% organic matter	0	1	6	0	0	1
Soil with >7% organic matter	1	2	3	3	6	0
Iron	0	0	13	0	0	10
Manganese	1	~	12	0	~	10
Zinc	4	3	6	0	0	10

Adapted from McKenzie 1992 and Solberg et al. 1999

Table 2.22 Species richness for each vegetation treatment on Cells 32 and 46

	Low	Medium	High	P Value
Cell 32	5 (3 to 8) [b]	8 (4 to 11) [a]	8 (4 to 13) [a]	0.000
Cell 46	5 (3 to 6) [b]	8 (4 to 12) [a]		0.003

Values reported as Mean (range)

Common letters in rows are not significantly different at ($p \leq 0.05$)

Cell 32 n = 20

Cell 46 n = 10

Table 2.23 Relative canopy cover (%) of vegetation species on Cell 32 in 2003

Common Name	Scientific Name	Relative Canopy Cover (%)
Sweetclover	*Melilotus* spp.	24.47
Perennial sow thistle	*Sonchus arvensis* L.	23.23
Fireweed	*Epilobium angustifolium* L.	18.97
Dandelion	*Taraxacum officinale* Weber	8.58
Common horsetail	*Equisetum arvense* L.	6.79
Wild red raspberry	*Rubus idaeus* L.	3.59
Bluejoint	*Calamagrostis canadensis* (Michx.) Beauv.	2.32
Alfalfa	*Medicago sativa* L.	2.25
Common yarrow	*Achillea millefolium* L.	1.99
Slender wheatgrass	*Agropyron trachycaulum* (Link) Malte.	1.63
Narrow leaf hawkweed	*Hieracium umbellatum* L.	1.27
Foxtail barley	*Hordeum jubatum* L.	1.18
Fowl bluegrass	*Poa palustris* L.	0.74
Horsetail	*Equisetum scirpoides* Michx.	0.65
Tufted hairgrass	*Deschampsia caespitosa* (L.) Beauv.	0.52
Northern wheatgrass	*Agropyron dasystachyum* (Hook.) Scribn.	0.35
Balsam poplar	*Populus balsamifera* L.	0.28
Wild strawberry	*Fragaria virginiana* Duchesne	0.24
Ticklegrass	*Agrostis scabra* Willd.	0.19
Rough cinquefoil	*Potentilla norvegica* L.	0.14
Smooth brome	*Bromus inermis* Leyss.	0.09
Long leaved chickweed	*Stellaria longifolia* Muhl.	0.09
Woodland horsetail	*Equisetum sylvaticum* L.	0.08
Carex	*Carex* spp.	0.06
Geranium	*Geranium bicknellii* Britt.	0.06
Wild vetch	*Vicia americana* Muhl.	0.06
Aster species	*Aster* spp.	0.03
Kentucky bluegrass	*Poa pratensis* L.	0.03
Bluegrass	*Poa* spp.	0.03
Clover	*Trifolium* spp.	0.03
Lamb's quarters	*Chenopodium album* L.	0.03
Wild mint	*Mentha* spp. L.	0.01
Narrow leaf willow	*Salix exigua* Nutt.	0.01
Alsike clover	*Trifolium hybrium* L.	0.01

Table 2.24 Species indicator values for each vegetation treatment preference for Cells 32 and 46 in 2003

Vegetaion Treatment Preference Species	Observed Indicator Value	Monte Carlo Simulation Mean (±SD) of Indicator Value	P Value
High Cell 32			
Melilotus spp.	69.2	35.8 (5.4)	0.001
Agropyron trachycaulum	37.7	15.1 (4.7)	0.002
Epilobium angustifolium	54.3	33.4 (5.1)	0.002
Equisetum arvense	47.2	34.7 (4.2)	0.007
Sonchus arvensis	45.3	37.9 (3.1)	0.017
Rubus idaeus	29.6	16.7 (5.9)	0.039
Agropyron dasystachyum	14.8	6.9 (3.4)	0.043
Medium Cell 32			
Agrostis scabra	23.8	12.0 (4.6)	0.021
Medium Cell 46			
Calamagrostis canadensis	88.6	43.6 (9.7)	0.003
Carex spp. #1	48.3	21.3 (8.0)	0.009
Sonchus arvensis	72.3	54.3 (6.8)	0.016
Achillea millefolium	48.4	29.1 (8.8)	0.036
Vicia americana	30.0	13.5 (6.1)	0.045
Tussilago spp.	30.0	15.1 (5.9)	0.050

Treatment Preference = Identifier for treatment with maximum observed indicator value
Observed Indicator Value = % of perfect indication based on combining values for relative abundance and relative frequency
P Value = Proportion of randomized trials with indicator value equal to or exceeding the observed indicator value

Table 2.25 Relative canopy cover (%) of vegetation species on Cell 46 in 2003

Common Name	Scientific Name	Relative Canopy Cover (%)
Bluejoint	*Calamagrostis canadensis* (Michx.) Beauv.	31.39
Perennial sow thistle	*Sonchus arvensis* L.	24.32
Fireweed	*Epilobium angustifolium* L.	10.39
Common horsetail	*Equisetum arvense* L.	9.48
Common yarrow	*Achillea millefolium* L.	3.50
Narrow leaf hawkweed	*Hieracium umbellatum* L.	2.99
Ticklegrass	*Agrostis scabra* Willd.	2.96
Carex species #1	*Carex* spp.	2.65
Willow spp.	*Salix* spp.	1.36
Unknown #2		1.36
Dandelion	*Taraxacum officinale* Weber	1.29
Kentucky bluegrass	*Poa pratensis* L.	1.22
Wild vetch	*Vicia americana* Muhl.	1.19
Carex species #2	*Carex* spp.	1.15
Coltsfoot	*Tussilago* L.	1.09
Horestail	*Equisetum scirpoides* Michx.	0.61
Narrow leaf hawk's-beard	*Crepis tectorum* L.	0.51
Aster species	*Aster* spp.	0.34
Canada buffaloberry	*Shepherdia canadensis* (L.) Nutt.	0.34
Unknown #1		0.34
Fowl bluegrass	*Poa palustris* L.	0.27
Long leaved chickweed	*Stellaria longifolia* Muhl.	0.24
Carex species #3	*Carex* spp.	0.20
Carex species #4	*Carex* spp.	0.20
Lamb's quarters	*Chenopodium album* L.	0.20
Trembling aspen	*Populus tremuloides* Michx.	0.17
Rush	*Juncus* spp.	0.07
Balsam poplar	*Populus balsamifera* L.	0.07
Rough cinquefoil	*Potentilla norvegica* L.	0.07
Wild red raspberry	*Rubus idaeus* L.	0.03

CHAPTER III. VEGETATION AND SOIL MOISTURE INTERACTIONS ON A TAILINGS SAND STORAGE FACILITY

1.0 INTRODUCTION

Soil water may be the most important requirement for vegetation not only because plants need water for their physiological development, but also because water often contains nutrients in solution essential for growth (Troeh and Thompson 1993). A fine balance exists within the interactions of soil, water and vegetation. If soils are saturated or above field capacity, oxygen diffusion into and within the soil is poor, and plants may suffer reduced growth or even death. Barrett-Lennard (1986) suggested that in areas of saturated and saline soil, plants exhibited enhanced uptake of sodium and chloride ions to the shoots; thereby, causing shoot senescence and adversely affecting growth. If soil moisture levels are below plant wilting point, plants cannot satisfy their water demands and exhibit reduced growth and perhaps death.

Capillary barriers play a critical role in soil moisture regimes within a reclamation setting. Essentially, capillary barriers are formed by multi-layered soil covers that restrict water movement and oxygen. They in fact are preferred in a reclamation setting for landfills, hazardous waste sites, acid generating waste rock and mine tailings impoundments for those reasons (Simms and Yanful 1999). Where mining produces waste rocks that contains high levels of sulphide, that when exposed to oxygen and water react to form sulphric acid, a capillary barrier is preferred to limit the infiltration of oxygen and water (O'Kane et al. 1998). In this case, a capillary barrier results from the compaction of a fine grained soil to achieve a high degree of densification and low hydraulic conductivity between two coarser grained soils, to acting as an evaporation and drainage barrier (Simms and Yanful 1999).

Within oil sands tailings reclamation the capillary barrier is not only formed from compacted soil layers and/or other impermeable materials, but from the mere presence of one soil texture overlying another, e.g., at the interface between an a fine textured soil (near-surface reclamation soil) and the underlying coarse textured material (tailings sand). Tailings sand, affected by tailings water, is generally considered to be an inappropriate growth medium, in itself. It functions as a capillary barrier because water in

the small pores of the reclamation soil is held at high tension and will not flow into the large pores of the coarse textured tailings sand where the water tension is low, until such time as the moisture content of the reclamation material is high enough (tension low enough) for water to flow into the underlying material (Porro 2001). With the establishment of vegetation, transpiration by plants recycles soil water back into the atmosphere during the growing season, thereby preventing its percolation into and through the tailings material. In areas with soil moisture deficits (precipitation < potential evapotranspiration) capillary barriers have the added effect of increasing the fraction of available water for plant use by limiting percolation. In addition, capillary barriers can also limit the upward migration of saline tailings water into the reclamation soil cover. Rooney et al. (1998) suggested capillary barriers effectively prevented upward migration of saline waters from brine wastes into the reclamation topsoil layer thus allowing vegetation to establish.

Previous research in soil moisture related to reclamation of oil sand tailings focused on the soil moisture properties of different soil amendments used for reclamation (Moskal 1999) and characterizing the soil moisture regime of Cell 32 (Chaikowsky 2003). The dynamic interactions of vegetation, soil moisture and the reclaimed tailings sand environment have not been studied at a field scale. To address this gap, this study examined the interactions of soil moisture and plant communities on the South West Sand Storage facility at Syncrude (SWSS), and aims to provide a comprehensive link between soil moisture and revegetation. As oil sands mining continues, the knowledge base for successful reclamation methods must be expanded so that the structure and function of the disturbed ecosystem can be restored and desired end land use obtained.

2.0 OBJECTIVES

The overall objective of this study is to characterize the interactions of soil moisture and the plant community. Research questions of specific interest include the following.

- Does surface soil moisture vary under different vegetation canopy covers?
- Does soil moisture vary above the soil / tailings sand interface under different canopy covers?

- Does soil moisture vary below the soil / tailings sand interface under different canopy covers?
- How does the soil moisture under different vegetation canopy covers respond to precipitation events?

3.0 MATERIALS AND METHODS

3.1 Study Area

The study area is located in the Athabasca oil sands deposit, approximately 50 km north of Fort McMurray, Alberta at Syncrude's Mildred Lake facility (Figure 2.1). The study area has short, cool summers with long, cold winters. Mean annual temperature is 0.7 °C with January being the coldest month (-18.8 °C) and July the warmest (16.8 °C) (Environment Canada 2003). Mean annual precipitation is 455.5 mm, with 342.2 mm occurring as rain and 155.8 cm as snow (Table 3.1).

Within the Athabasca oil sands the ore bearing materials originate from the Cretaceous Period McMurray Formation, developed through deposition of organic material within fluvial and tidal conditions (Wedage et al. 1998). The overall thickness of the McMurray Formation varies depending on underlying unconformity but its maximum thickness is over 150 m (Flach 1984). The McMurray Formation is underlain by shales and limestones of the Waterways Formation (Devonian) and overlain by marine shale and sandstone of the Clearwater Formation (Conly et al. 2002). Above the Clearwater Formation, marine sandstone from the Grand Rapids Formation dominates (Flach 1984).

The characteristic mineral soils in the upper slope positions are Orthic Gray Luvisols with transitions to Gleyed Gray Luvisols in mid to lower slope positions (Turchenek and Lindsay 1982). In low or toe slope positions Gleysolic soils dominate and Organic soils are present within depressions. Fibrisols and Mesisols are the most commonly occurring great groups in the study area (Turchenek and Lindsay 1982).

The natural vegetation of the area is typical of the Boreal Mixedwood Ecological area (Alberta Environmental Protection 1994). The upland areas are primarily composed of deciduous forests with the dominant tree species being trembling aspen (*Populus tremuloides* Michx.) and balsam poplar (*Populus balsamifera* L.). On drier, sandier sites communities of jack pine (*Pinus banksiana* Lamb.) dominate. Within lowlands the

dominant tree species are black spruce (*Picea mariana* (Mill.) BSP), white birch (*Betula papyrifera* Marsh.) and tamarack (*Larix laricina* (Du Roi) K. Koch).

3.2 Study Site

3.2.1 South West Sand Storage Facility

The SWSS is a 25 km^2 hydraulically filled tailings sand storage facility, located in the southwest corner of Syncrude's Lease 17 (Figure 3.2). Tailings are produced through the bitumen extraction process; they are the remaining ore body after the bitumen has been removed and thus contain a large fraction of sand. The sand is 96 to 99% SiO_2, 0.5 to 0.9% Al_2O_3 and 0.1 to 0.9% Fe (Mikula et al. 1996). With this coarse sand, water, clay particles, silt and a minor fraction of residual hydrocarbons form the tailings material. Water is introduced through the Clark hot-water extraction process and becomes high in chlorides, sulphates and sodium. Clay particles and silt are from overburden material admixed with the ore during mining. Residual hydrocarbons result from the extraction process which is approximately 96% efficient. The SWSS receives the tailings sand, transported in slurry form, from the extraction plant via a network of pipes and pumps. This slurry is allowed to settle and dewater until it is practical for machinery to redistribute the sand material.

The SWSS became operational in 1991 with the establishment of a perimeter dyke, which was then followed by an ongoing process of cell construction (AGRA 1997). It currently holds an estimated 500 million m^3 of tailings sand and upon closure will hold over 800 million m^3 (Syncrude 2004). The construction of cells includes the formation of terraced slopes with backslopes (or benches) from the toe ditch to the beach. Spillways (or swales) collect surface water and transport it from the structure to the toe ditch. The SWSS was designed to have an external overall slope of 20H:1V to ensure stability of the structure (AGRA 1997). Once the tailings material is placed, reclamation is initiated on the slopes with the placement of reclamation soils, fertilizer application and revegetation. The SWSS presents distinctive reclamation challenges in its massive size and its construction without internal drains which may result in tailings water seeping from the dyke into the reclamation soils, which could affect soil and vegetation reclamation success.

3.2.2 Cell 32

Cell 32, a 2.5 km^2 area on the east side of the SWSS (Figure 3.3), consists of 4 slopes, 3 backslopes, a flat area at the toe and a beach at the top (Figure 2.4). Slopes are approximately 90 m in length and graded to 10%. Backslopes are approximately 80 m in length and graded to 2%. This study utilized the first bottom slope (Figure 2.4). On the backslopes, constructed waterways collect runoff and seepage water and are designed to transfer it laterally to the swale that forms the southern boundary of the site. The water is then transferred down the swale to the toe ditch that collects water from the base of the SWSS.

The cell is undergoing progressive reclamation which started in 1995 with the placement of reclamation soil material. The reclamation soil material was designed to have an 80 cm depth and consisted of a peat secondary mix. This material was salvaged from pre-mined areas and is a mixture of peat and mineral materials resulting in a mineral soil (<17% organic carbon dry weight basis). It was obtained by either overstripping peat into the mineral soil, or by placing peat material and then rotovating into underlying mineral material (Yarmuch 2003).

After the reclamation soil placement the area was fertilized with a 10-30-15-4 mix, applied at a rate of 364 kg/ha. Reforestation occurred in fall 1996 with the planting of trembling aspen, white spruce, jack pine, red-osier dogwood (*Cornus stolonifera* Michx.), hybrid poplar (species unknown) and Siberian larch (*Larix sibirica* Ledeb.) at an average stem density of 2,000 stems/ha. Jack pine was planted only along the crest lines on the slopes and backslopes (Earl Anderson 2003).

3.3 Meteorological Parameters

Meteorological data for 2003, 2004 and the long term climate normal from 1971 to 2000 were obtained from the Environment Canada monitoring station located at the Fort McMurray Airport (56° 39' N and 111° 13' W). In addition a meteorological station was installed on the upper back slope of Cell 32 by O'Kane Consultants Inc. Air temperature, solar radiation, precipitation, relative humidity, wind speed and wind direction were recorded hourly. Although the station did record snow fall, due to the large

discrepancy in the data from Cell 32 and the Environment Canada station, caution is suggested in the interpretation of the total precipitation data from Cell 32.

3.4 Soil Moisture

Soil moisture was measured in situ with Campbell Scientific CS615 Water Content Reflectometers, using time-domain reflectometry methods (TDR probes), interfaced with Campbell Scientific CR10X dataloggers. TDR technology makes use of the unique electrical properties of the water molecule (Topp 1993). TDR probes determine the dielectric constant by measuring the propagation time of electromagnetic waves sent through a known length of medium (Noborio 2001). The travel time of the electromagnetic waves is dependent on the dielectric constant of the measured medium. Air, soil and water have dielectric constants of 1, 2 to 7 and 80, respectively (Topp 1993). It would therefore take the electromagnetic waves longer to travel through water than air, since the velocity of propagation is decreased in materials of higher dielectric constants (Topp 1993).

The study used 24 TDR probes in two separate locations on the lower forward slope of Cell 32. Each location consisted of four TDR nests, where two nests were installed into low vegetation plots and two nests were installed into high vegetation plots (Figure 3.5 and 3.6). Within each nest a probe was inserted at a 45^0 angle into top 15 cm of the topsoil, horizontally 10 cm above the tailings sand / reclamation soil interface and horizontally 10 cm below the interface into the tailings sand (Figure 3.7). A pit approximately 1 x 1 m was dug to facilitate the insertion of probes at the two lower depths. Probes were inserted upslope into the undisturbed reclamation soil and tailings sand and then the pits were carefully backfilled.

The TDR probes were laboratory calibrated with the reclamation soil and the tailings sand from the study site by O'Kane Consultants Inc. Calibration equations were determined so that the dataloggers output (mV) could be converted to soil volumetric moisture content (VMC). Measurements were made on an hourly basis from the start of the study, July 2003, until the end, October 2004, but only results from after soil thawed and before it froze were considered.

3.5 Vegetation

Vegetation parameters were assessed within the high and low vegetation nests using 0.1 m^2 (0.2 x 0.5 m) quadrats. In each quadrat, plant species composition and plant species distribution were assessed through ground cover (% bare ground, % litter and % live vegetation), total canopy cover and canopy cover by species. Total canopy cover was measured by looking down on the canopy and not moving any of the vegetation to determine overlap. Individual species canopy cover was measured as the total canopy cover of each species within the quadrat. Quadrats were located directly above the surface soil moisture probes so calibrations could be made between vegetation parameters and soil moisture at the precise location of measurement.

3.6 Soil Chemistry

Soil was sampled in August 2004 at the geographic center of each vegetation plot, corresponding to the location of the vegetation assessment. Sampling was conducted using a 5.08 cm Dutch auger at 0 to 10 cm, 10 to 20 cm and then at 20 cm depth intervals until the tailings sand was reached, after which one additional 20 cm depth sample was obtained from the tailings sand. Three adjacent holes were needed to obtain the required volume of sample for the 0 to 10 cm and 10 to 20 cm depth intervals. These adjacent holes were placed within the area of vegetation assessment and the central hole was used for the remaining depth intervals. All samples were composited from their depth intervals, placed in a cooler within 1 hour and kept cool until laboratory analyses. The soil samples were analyzed at EnviroTest Laboratories, Edmonton, for percent saturation, pH, electrical conductivity, sodium adsorption ratio (SAR), cations (calcium, potassium, magnesium and sodium) and anions (chloride, nitrate, nitrite, sulphate and phosphate) from a saturated paste extract (Janzen 1993). Plant available nitrogen analysis was performed with an extract of $CaCl_2$ (Maynard and Kalra 1993) and plant available phosphorus was determined with the modified Kelowna extract method (Qian et al. 1994). Additional analyses on the 0 to 10 and 10 to 20 cm depth intervals included DTPA extractable micronutrients copper, iron, manganese and zinc (Liang and Karamanos

1993) and organic matter and organic carbon by the wet oxidation-redox titration method (Tiessen and Moir 1993).

3.7 Soil Physical Properties

Water holding capacity was determined at 10 and 33 kPa to represent field capacity for the tailings sand and reclamation soil, respectively. The water retention was also determined at 1500 kPa to represent wilting point for the tailings sand and reclamation soil. Depth to the tailings sand was measured and recorded during the TDR installation to denote the depth of reclamation soil.

3.8 Statistical Analyses

Statistical comparisons were performed using a non-parametric Mann-Whitney test (Zar 1999) with SYSTAT statistical software. The Mann-Whitney test is identical to the Kruskal-Wallis test, but is desirable when two treatments are compared (Zar 1999). Preliminary analysis indicated that the soils and vegetation data were non normal. Despite the application of different transformations, the data remained non normal, in part due to the small sample sizes (8 for the surface and 4 each for above and below the interface). Thus a non parametric test was selected to test the null hypothesis that vegetation and soil parameters were the same between the TDR nests under low and high vegetation canopy cover. A confidence level of 95% was chosen ($\alpha = 0.05$) to distinguish statistically significant variation.

4.0 Results and Discussion

4.1 Meteorological Parameters

In 2003 mean temperature was similar to the long term climate normal (LTN) (Environment Canada 2004) (Tables 2.1, 2.3, 2.4 and 2.5). Mean temperatures in 2003 at the airport were higher in January, July, August and December but lower in February and March compared to the LTN, for the remaining months the mean temperatures were similar. Total precipitation in 2003 (375.1 mm) was slightly above the LTN (342.2 mm) but more precipitation fell during the months of May and June and less fell during July and August. In September total precipitation was substantially greater (89.4 mm)

compared to the LTN (46.8 mm). Temperature and precipitation from Cell 32 showed a similar trend to that at the airport.

In 2004 the mean temperature for the airport and Cells 32 were similar to the LTN. The mean temperature in 2004 was higher in February and July but lower in January, May and from August to October than the LTN. Total precipitation in 2004 was less from January to July (200.3 mm) compared to the LTN (265.1 mm).

4.2 Vegetation

In 2003 there was a significant difference in total canopy cover between the low (15%) and high vegetation nests (72%) (Table 3.4). Within the ground cover, there was also a significant difference for live vegetation between the low (1%) and high (4%) vegetation nests. For all other vegetation parameters there were no statistically significant differences.

The species with the highest relative canopy cover in the low vegetation nests were fireweed (*Epilobium angustifolium* L.) (30%), wild red raspberry (*Rubus idaeus* L.) (21%), and perennial sow thistle (*Sonchus arvensis* L.) (15%). For the high vegetation nests the species with the highest relative canopy cover were wild red raspberry (29%), fireweed (21%) and sweetclover (*Melilotus* spp.) (20%). Canopy covers in 2004 were similar to those in 2003 except for location 1D, in the high vegetation nests, where total canopy cover was reduced due to an animal bedding on top of the assessment area. The rooting depth for most plants was within <30 cm for the plots visually determined through the TDR installation and soil sampling.

4.3 Soil Chemistry

At the surface SAR was significantly different between low (1.2) and high vegetation nests (0.7) (Table 3.5). Sodium also differed significantly between low (46 mg/L) and high (26 mg/L) vegetation nests. For all other parameters there were no statistically significant differences.

Above the interface magnesium differed significantly between low (14 mg/L) and high (105 mg/L) vegetation nests (Table 3.6). Calcium was significantly different between low (64 mg/L) and high (513 mg/L) vegetation nests. Potassium was also

significantly different between low (3 mg/L) and high (7 mg/L) vegetation nests. For all other parameters there was not a statistically significant difference. It is evident that soil chemical properties have higher concentrations above the interface than at the surface (Tables 3.5 and 3.6). For the high vegetation nests, sulphate, sodium and magnesium concentrations above the interface were substantially higher than at the surface for the same sites. In the low vegetation nests, sulphate and sodium had substantially higher concentrations above the interface than at the surface for the same sites.

Below the interface electrical conductivities differed significantly between the low (0.4 dS/m) and high (1.0 dS/m) vegetation nests (Table 3.7). SAR was also significantly different between low (1.7) and high (1.0) vegetation nests. Magnesium, calcium and potassium were all significantly higher in the high vegetation nests. For all other parameters there were no statistically significant differences.

The soil chemistry results were expected. The differences in SAR at the surface and below the interface are due to differences in sodium, magnesium and calcium concentrations. The main concern with the use of TDR probes and soil chemistry is the electrical conductivity of the soil solution. Some researchers suggest that at higher levels of salinity TDR measurements can over estimate soil water content. Within the literature it is disputed at what levels electrical conductivity can affect TDR measurements and increase errors in the determination of soil water content. Hook et al. (2004) in a study investigating the influence of salinity on the accuracy of different soil water measurements found that measurement errors were associated with electrical conductivities > 25 dS/m. This is contradicted by Jackson (2004) who found that salinity can enhance TDR measurement errors at salinity levels > 1 dS/m. Nadler et al. (1999) suggested TDR measurements are accurate at EC levels < 2 dS/m. In this study, the highest recorded electrical conductivity was 3.2 dS/m and it was located above the interface in the high vegetation nest, site 1B. Also in the high vegetation nests above the interface, locations 1C and 2D had electrical conductivities of 2.5 dS/m and 2.9 dS/m, respectively. Caution should therefore be used in the interpretation of the data for the high vegetation nest above the interface as salinity may have resulted in an over estimation of soil VMC at this location.

4.4 Soil Physical Properties

For the reclamation soil, field capacity was 0.201 g/g and the wilting point was 0.074 g/g. The average bulk density from Chaikowsky (2003) was 1.38 Mg/m^3, which yields a field capacity and wilting point, on a volume basis, of 27.7 and 10.2%, respectively. For the tailings sand the field capacity was 0.073 g/g and the wilting point was 0.0075 g/g. The average bulk density for the tailings sand from Chaikowsky (2003) was 1.18 Mg/m^3, which yields a field capacity and wilting point, on a volume basis, of 8.6 and 0.9%, respectively.

The average depth to the tailings sand interface in the low vegetation nests ranged from 52 to 98 cm and from 49 to 71 cm in the high vegetation nests. The average depth for the low (78 cm) was not significantly different from that of the high vegetation nests (83 cm) (Table 3.5).

4.5 Surface Soil Moisture

In 2003 the average surface VMC for the low vegetation nests ranged from 16 to 38%, with a decrease in VMC from July to August, then an increase in VMC in September that coincided with increased precipitation (Figure 3.8). The high vegetation nests had a VMC range from 9 to 29%. The average trend was a decrease in VMC from July to September and then an increase in VMC in September that coincided with precipitation. In general the high vegetation nests had lower VMC than the low nests from July until late October at which time the soil froze.

In 2004 the average surface VMC for the low vegetation nests ranged from 8 to 28% after the soil thawed in early April (Figure 3.9). In mid March higher air temperatures contributed to snowmelt, which increased average VMC to a maximum of 14%. For high vegetation nests a similar trend occurred with a range from 8 to 28%. A difference exists in the larger magnitude of the mid March thaw where the average VMC maximum was 23%, suggesting that high vegetation nests trapped a greater amount of snow, that when melted, contributed to higher VMC.

In general low and high vegetation nests had similar VMC patterns but differences occurred between vegetation nests. In mid March and from late April to late May low vegetation nests had lower VMC. From late May to early July low vegetation

nests had higher surface VMC. For the rest of the year the two vegetation treatments had similar VMC.

In summary, throughout the growing season, May to August, low vegetation nests had greater VMC values than the high vegetation nests averaging 11.6% and 0.3% in 2003 and 2004, respectively. Differences in VMC between vegetation nests could be explained through lower evapotranspiration and/or interception in the low vegetation nests. Evapotranspiration is often a significant component in the hydrologic cycle and soil water balance. Grelle et al. (1997), in a study in the boreal forest of Sweden, demonstrated that transpiration accounts for the largest contribution to total evaporation with maximum values of approximately 4 mm per day. They estimated that of the accumulated components, transpiration constituted 65%, forest floor evaporation 15% and interception evaporation 20% of the total forest evaporation observed during the study. Lundblad and Lindroth (2002), also studied boreal forest stands in Sweden to determine soil moisture dependences, and found transpiration constituted 78% of total evaporation in the warm, dry season and 52% in the wet, cool season. Similarly Blanken (1997) in a study of southern boreal forests in Saskatchewan found evapotranspiration from the forest accounted for 82 to 91% of the annual precipitation.

Although transpiration is important, Lagergren and Lindroth (2002) stated that it is inherently difficult to establish a firm relationship between transpiration and soil water content, mainly because of the large spatial variation in soil properties and soil moisture and because of transpiration's strong dependence on microclimate parameters. Lundblad and Lindroth (2002) also found that it was not possible to establish, with confidence, a critical limit for soil water at which transpiration began to be reduced, mainly because of large variation in the relationship between potential and actual transpiration. In this study the differences in soil moisture and the cause and effect relationship with evapotranspiration are presented with the assumption of similar microclimates and soil parameters between vegetation nests with total canopy cover explaining the variations observed.

The differences in VMC could also be explained from the different levels of rainfall interception between low and high vegetation nests. The interception of precipitation by vegetation canopies may have important influences on ground surface

hydrology (Dunkerley and Booth 1999). Canopy interception can reduce the amount of precipitation directly contacting the soil surface thorough the direct physical blocking of precipitation by the vegetation canopy and the subsequent evaporation of this precipitation directly from the vegetation surface. Elliott et al. (1998), studying the effects of forest harvesting on soil moisture in the boreal forest of Saskatchewan, found the expected increased canopy interception with increased leaf area index. This suggests that the higher total canopy cover of the high vegetation nests may have greater interception than the low vegetation nests, resulting in increased soil moisture in the low vegetation nests. Although interception would occur within the high vegetation nests the overall effect on soil moisture may be reduced. Dunkerly and Booth (1999) suggested that because interception may temporarily reduce evapotranspiration and a significant proportion of intercepted water may be transported to the ground surface through stemflow, the overall effects of interception on soil moisture may be reduced.

In 2003, the low vegetation nests had soil moisture above field capacity from the start of the study to the end of July and from mid September, after a period of high precipitation, until the soil froze. In contrast, the high vegetation nests only had soil moisture above field capacity on July 6 and July 10. In 2004 both the low and high vegetation nests were above field capacity for only one day, May 30, which was the direct result of precipitations event of 4.3, 11.4 and18.5 mm on the 28, 29 and 30 of May, respectively.

At no time in 2003 did the low vegetation nests have VMC lower than wilting point, while the high vegetation nests had VMC below wilting point from August 24 to September 3. In 2004 the low vegetation nests had VMC below wilting point from July 1 to July 20, July 23 to July 27 and from August 3 to September 3, while the high vegetation nests were below wilting point from June 27 to July 20 and from July 29 to September 4.

4.6 Soil Moisture Above The Reclamation Soil / Tailings Sand Interface

In 2003 average VMC above the reclamation soil / tailings sand interface for the low vegetation nests ranged from 44 to 66%, with a decrease from July to the end of the year (Figure 3.10). The high vegetation nests ranged from 25 to 35% with decreasing

VMC from mid July to mid September at which time percolation from a large precipitation event increased VMC. In general the high vegetation nests had lower VMC above the interface from July until the end of the year. The low vegetation nests responded to precipitation events more than the high vegetation nests, suggesting there was less percolation under the higher vegetation nests. In general VMC above the interface was consistently higher than VMC at the surface for the same sites.

In 2004 VMC above the interface for the low vegetation nests ranged from 21 to 49%, with an average increase in VMC from spring thaw until the beginning of June, at which time VMC decreased throughout the growing season until mid July (Figure 3.11). Thereafter VMC remained fairly constant with small increases from precipitation events. High vegetation nests ranged from 17 to 39%, with increase in VMC from spring thaw until the beginning of June, at which time VMC decreased throughout the growing season until mid September, when it increased corresponding to a precipitation event. In general high vegetation nests had lower VMC from spring thaw until the end of the year. The low vegetation nests responded to precipitation events more than the high vegetation nests suggesting less percolation under high vegetation nests. In general VMC above the interface was consistently higher than at the surface, as in 2003.

VMC above 48% in 2003 at the low vegetation nests were not expected. With an average bulk density of 1.38 Mg/m^3 the average porosity would be 48% and VMC above 48% are physically impossible. A possible reason for the unexpected results could be a lower soil bulk density at these locations than the average bulk density. During installation of the probes there were masses of non decomposed peat, throughout the soil profiles. These peat masses would lower bulk density, thus increasing porosity and increasing soil water retention.

In 2003 soil moisture in the low vegetation nests above the interface was consistently above field capacity. Soil moisture at the high vegetation nests was below field capacity from August 28 to September 14 at which time a large precipitation event, 40.9 mm, returned soil moisture to above field capacity.

In 2004 soil moisture in the low vegetation nests was also consistently above field capacity from late April to the end of the study. The high vegetation nests were above

field capacity from May 2 to July 11 and below field capacity the remaining time. The high vegetation nests were never below wilting point at this depth.

The high vegetation nests being above field capacity for a shorter duration than the low vegetation nests implies less soil water was available from the surface to percolate through the soil profile under the high vegetation nests. This is best illustrated from July 19 to July 28, 2004 where a total of 19.0 mm of precipitation fell on Cell 32. The low vegetation nests demonstrated slightly increased VMC above the interface, while over the same time period, VMC decreased for the high vegetation nests (Figure 3.12). This suggests there was a decrease in percolation with depth under the high vegetation nest either from less moisture entering the soil and/or less moisture available for percolation.

4.7 Soil Moisture Below The Reclamation Soil / Tailings Sand Interface

In 2003 VMC below the interface for the low vegetation nests ranged from 5 to 17%, with a consistent VMC between 5 and 12% (Figure 3.13). Fluctuations in VMC appear to be caused by precipitation events. The high vegetation nests ranged from 2 to 8%, with a fairly consistent VMC throughout the year with increases under only the largest precipitation events. High vegetation nests had lower VMC from July until the end of the year. Low vegetation nests responded to precipitation events more than the high vegetation nests suggesting there was less percolation under high vegetation nests. VMC below the interface was consistently lower than above the interface for the same sites.

In 2004 VMC below the reclamation soil / tailings sand interface for the low vegetation nests ranged from 4 to 12% (Figure 3.14). Fluctuations in VMC were likely caused by precipitation events. The high vegetation nests ranged from 4 to 13%, with fluctuations in April and March from percolation of snowmelt during a warmer period. After this period, VMC ranged between 4 and 10%. High vegetation nests had higher VMC from March until the end of May at which time low vegetation nests had higher VMC. The low vegetation nests responded more to precipitation events than high vegetation nests suggesting less percolation occurred under high vegetation nests. In

general VMC below the interface were consistently lower than VMC for the same sites above the interface.

In 2003 soil moisture below the interface in the low vegetation nests was consistently above field capacity (8.0%) from July 10 to August 13 and from September 15 to December 13. High vegetation nests were never above field capacity. In 2004 soil moisture in the low vegetation nests were above field capacity from May 30 to June 27, on September 5 and from September 19 to September 25. The high vegetation nests were variable, with soil moisture above and below field capacity from early March until the end of April at which time values were above field capacity until May 27. Soil moisture was again quickly raised above field capacity on May 30 after precipitation events on May 28 and 29 which maintained soil moisture above field capacity until June 11. For the remainder of the year soil moisture was below field capacity.

Soil moisture below the interface was unexpected given the higher soil moisture above the interface. Soil moisture would be expected to move from areas with higher potential (above the interface), into areas with lower potential (below the interface) but this was not the case. The textural discontinuity at the interface appears to restrict water movement through the interface. Chaikowsky (2003) suggested that a possible reason for the restricted movement of water through the interface was the hydrophobic qualities of the tailings sand. The hypothesis was based on the findings that during pressure plate analysis, once the tailings sand was dried it was hard, if not impossible, to saturate. The 4% of bitumen remaining in the tailing sands mixture after extraction may cause hydrophobicity. Bauthers et al. (1997) suggested hydrophobic soils also exhibit unstable finger-like wetting fronts and water entry into hydrophobic soils only occurs after the depth of the ponded water above the hydrophobic soils equalled or exceeded the water-entry pressure, which increased with increasing hydrophobicity.

Decreased net soil water movement across the interface is also the result of different physical properties of tailings sand and the reclamation soil above. Troeh and Thompson (1993) suggested that in areas of contrasting soil layers, with a sand layer overlain by soil, water movement is not always in a manner that might be anticipated. They suggested that the pore spaces of sand have very small capillary potentials to draw water from a moist soil and that the capillary potential of the soil is stronger than that of

the sand. This results in water accumulation above the texture discontinuity and the soil above the sand becomes saturated with a moisture potential of zero. Troeh and Thompson (1993) suggested that when water finally enters the sand, it moves suddenly, rapidly and erratically, producing jagged finger-like wet zones as it drains part of the excess water accumulated in the soil above, resulting in a heterogeneous wetting pattern.

At the interface, the textural discontinuity created through the different physical properties of the reclamation soil and tailings sand not only restricts water movement into the tailings but may also restrict tailings water movement into the reclamation soil cover (Chanasyk 2004). In many tailings management operations it is desirable to limit movement of saline tailings water into the soil cover for the benefit of the reclamation soil and the vegetation established. In this study it was clear that tailings water was not moving into the reclamation soil as the TDR probes below the interface had consistently lower VMC than the probes over the interface. Macyk and Faught (2001) conducted a similar study north of Cell 32 on the SWSS near a swale, suggested tailings water is moving into the reclamation soil and concluded SAR and other chemical parameters have increased by as much as four-fold in the reclamation soil above the interface, as a direct result from tailings water entering the reclamation soil cover.

In this study, the hydrophobicity and/or the inherent different physical properties of the reclamation soil and tailings sand may explain why increases in soil moisture in the tailings sand only occurred after large precipitation events. An example of this occurred in late May 2004. On May 29 and 30 precipitation events of 11.4 and 18.5 mm increased soil moisture, in the tailings sand in the low vegetation nests, from antecedent values of 7.1 to 10.7% on May 31 (Figure 3.14). Similarly, in the high vegetation nests soil moisture increased from 7.6 to 9.2% on June 2 as a result of the precipitation events.

Similar events occurred on September 18 and 19, 2004 where precipitation events of 17.5 and 19.3 mm increased soil moisture in the low vegetation nests from 6.7 to 10.1% on September 19 (Figure 3.14). In the high vegetation nests soil moisture increased from 4.3 to 6.0% on September 19. This suggests that during periods of precipitation the textural discontinuity at the interface will result in precipitation water being held within the reclamation soil for longer periods of time. Over the last few years, which have been on average drier than normal, this would be beneficial for plant growth

as the textural discontinuity would hold the precipitation water for a longer period of time thus increasing the ability of plants to use this water.

The TDR probes in the high vegetation nests recorded higher soil moisture in the tailings sand almost immediately after the precipitation event on September 18, 2004 as compared to May where soil moisture increase 4 days after the May 28 precipitation event. This could be explained by the dormancy of vegetation in September, as the vegetation was past the peak of the growing season and thus required less water, leaving more water available for percolation the tailings sand. This is supported by the other precipitation events ($\geq$ 5.8 mm) throughout the growing season in 2004 (July 20, July 27 and August 8) that increased soil moisture below the interface in low vegetation nests but not in high vegetation nests. A similar pattern of increased soil moisture in low versus high vegetation nests, after precipitation events, was also evident in the sensors at the surface and above the interface.

5.0 CONCLUSIONS

VMC was highest in the low vegetation nests at the surface, above and below the reclamation soil / tailings sand interface, but excess soil moisture or saturated conditions were not negatively impacting vegetation. Vegetation experienced periods of water stress (VMC below wilting point) but these periods were of short duration and also typical of boreal forest ecosystems.

The difference in soil moisture at the surface was attributed to differences in evapotranspiration and/or canopy interception between vegetation nests. Differences above and below the interface were caused by different canopy covers at the surface and resulting differences in quantity of water available for percolation through the soil profiles.

At the interface of the reclamation soil and tailings sand, water movement is restricted. The inherent differences in physical properties of the reclamation soil and tailings sand and/or possible hydrophobicity of the tailings material would explain this restriction. The implications for vegetation were increased water availability in the reclamation soil and the possible buildup of ions above the interface.

Different canopy covers responded differently to precipitation events and the low vegetation nests exhibited greater fluctuations in VMC, at all depths, in response to precipitation events.

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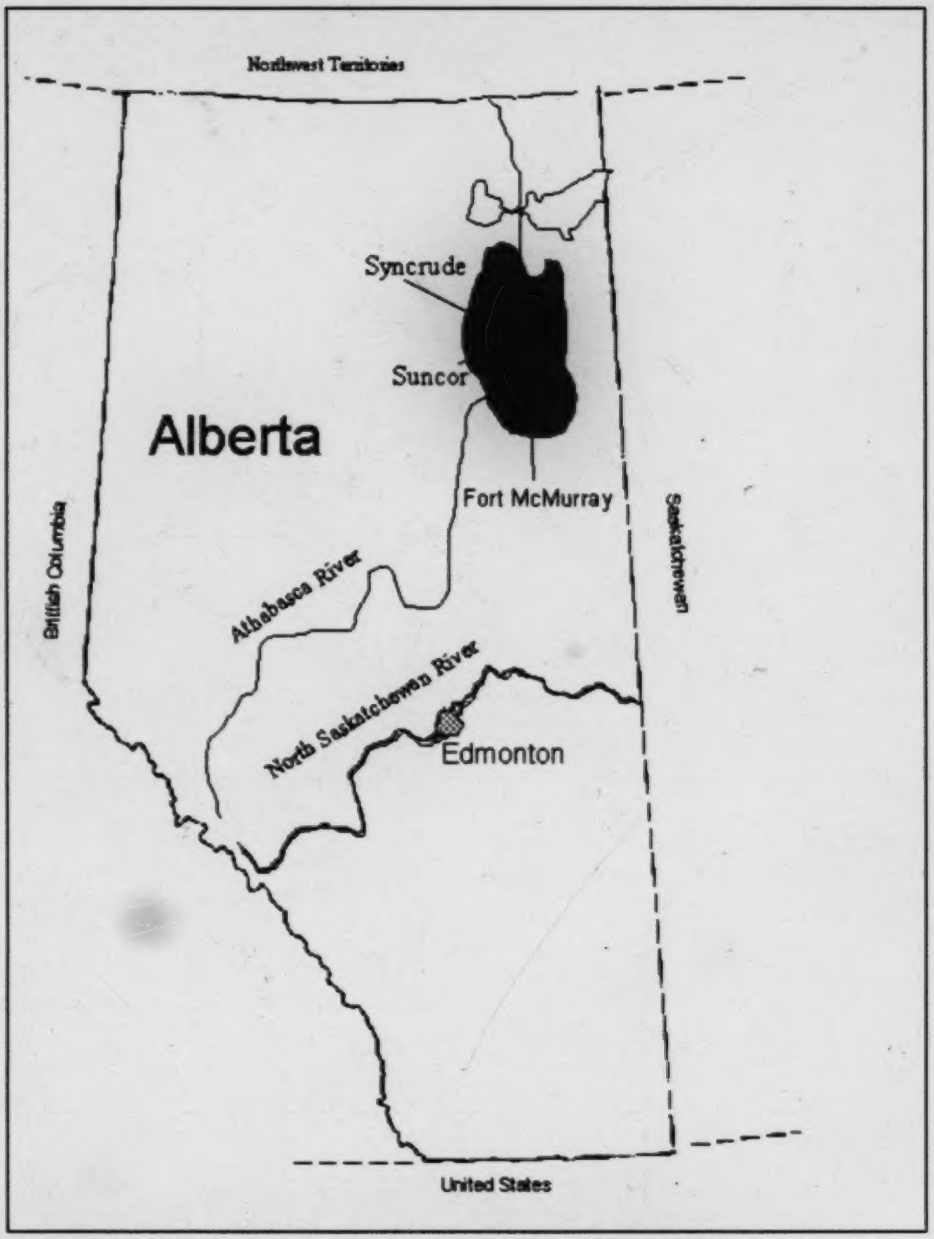

Figure 3.1 Map of study area (adapted from OSERN 2004)

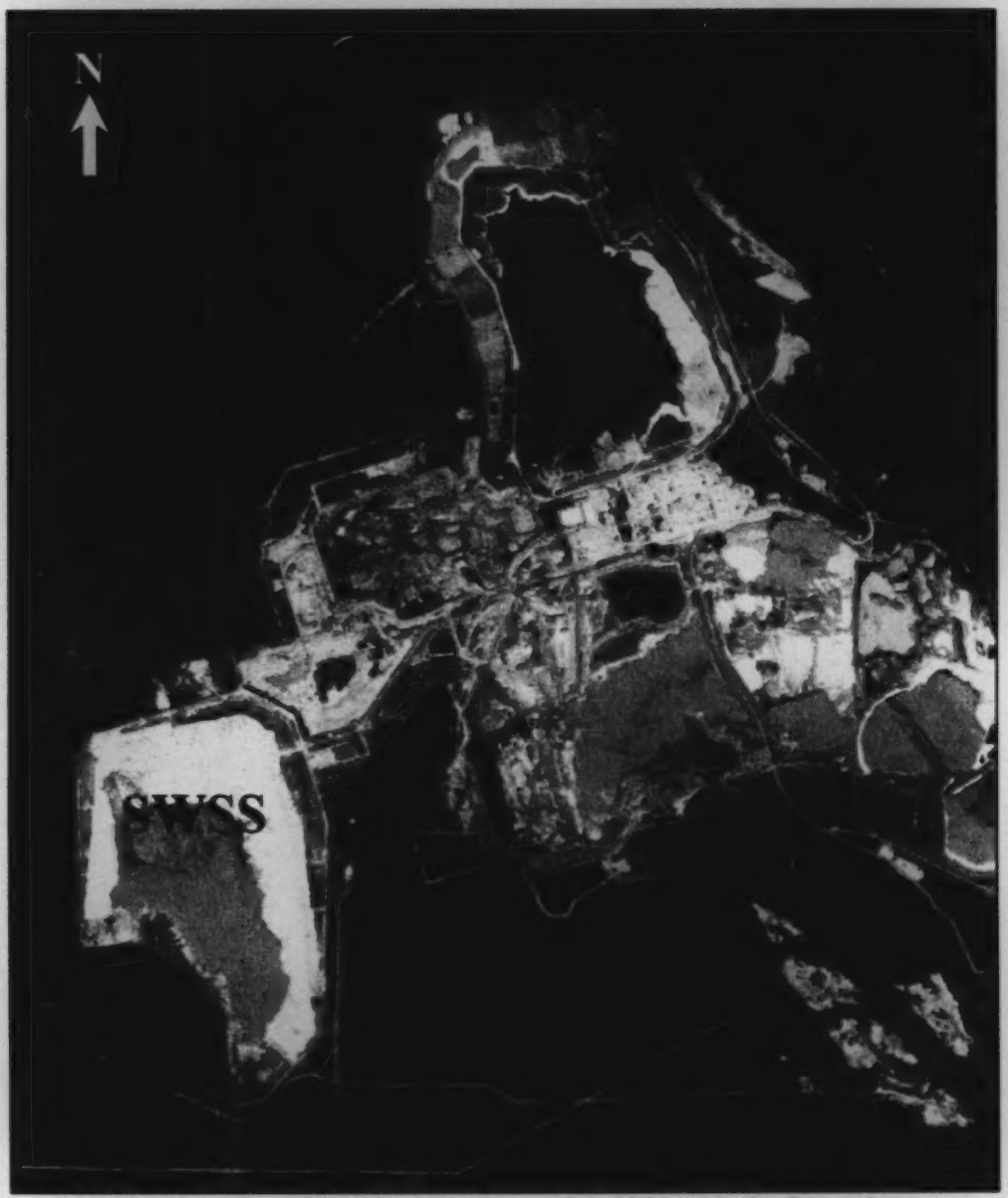

Figure 3.2 **Location of SWSS within Syncrude's Mildred Lake Operation (adapted from Syncrude Canada Ltd.)**

Figure 3.3 **Location of Cell 32 on the SWSS (adapted from Syncrude Canada Ltd.)**

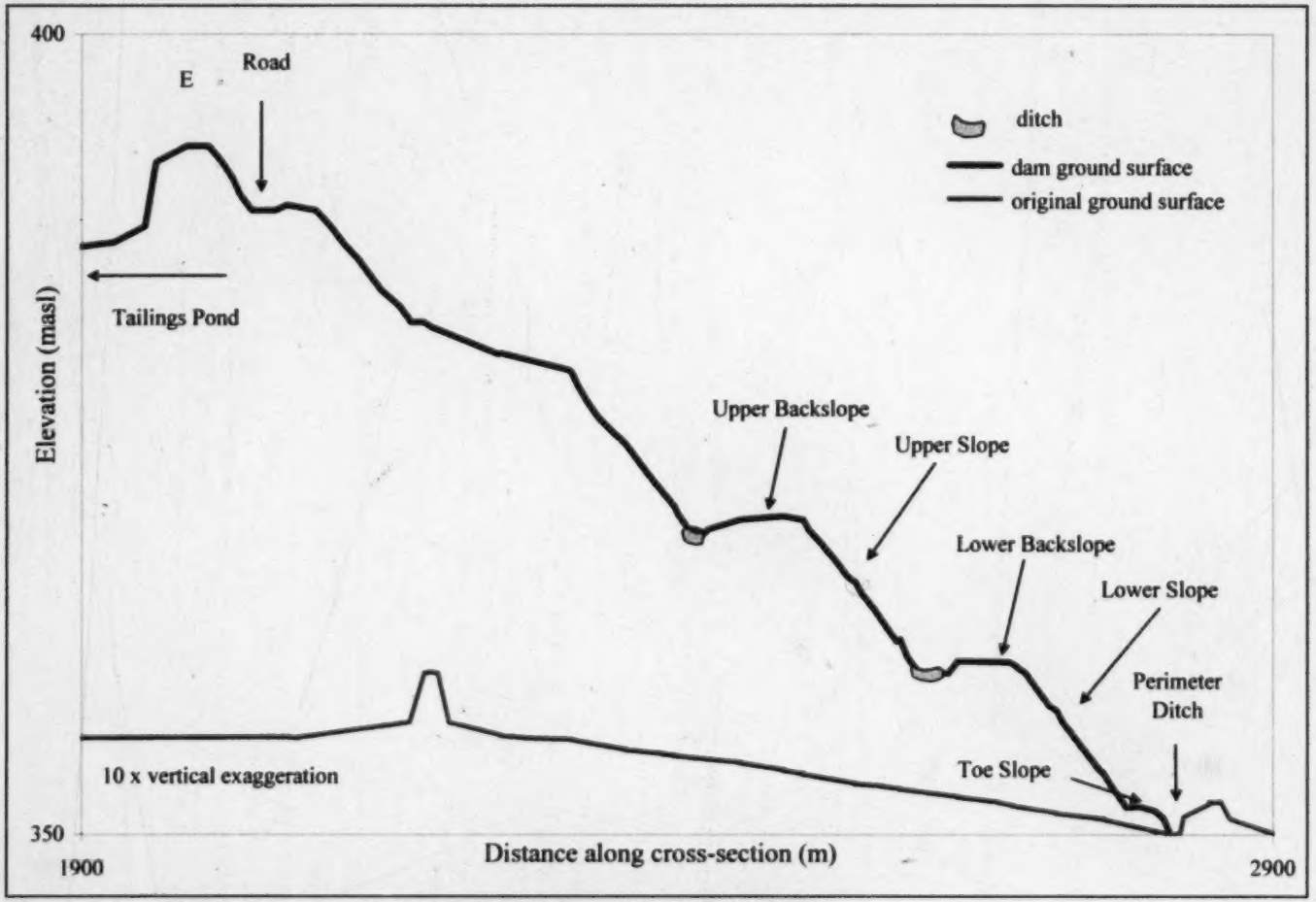

Figure 3.4 Vertical cross-section of Cell 32 (adapted from Price 2004)

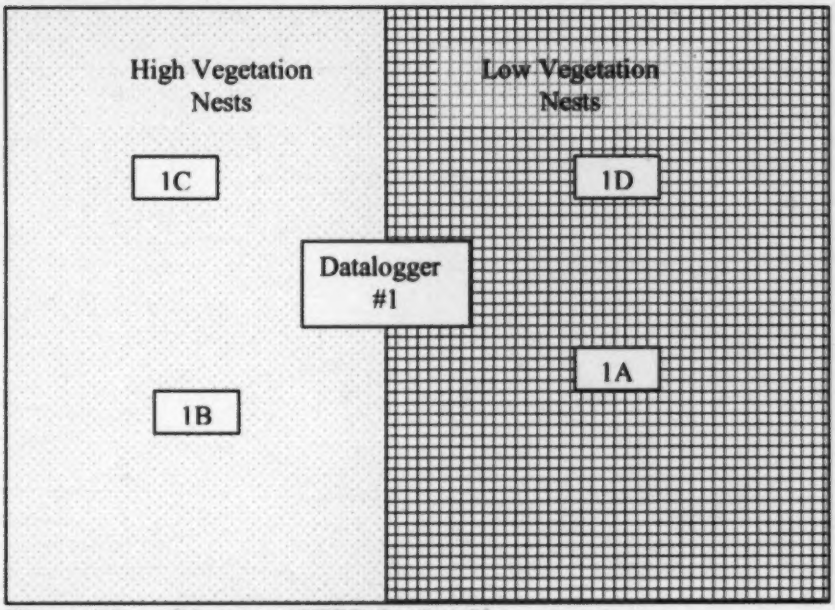

Figure 3.5 Diagram of TDR Station #1

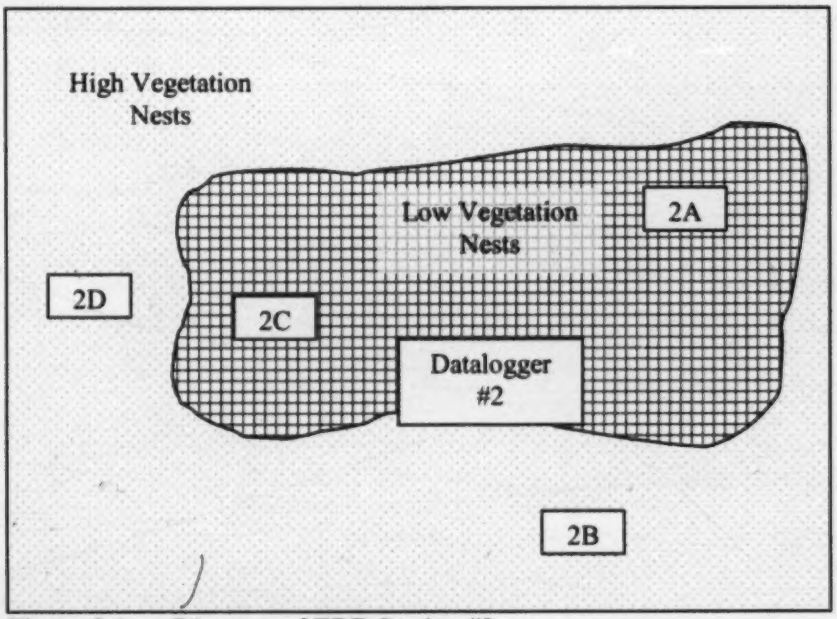

Figure 3.6 Diagram of TDR Station #2

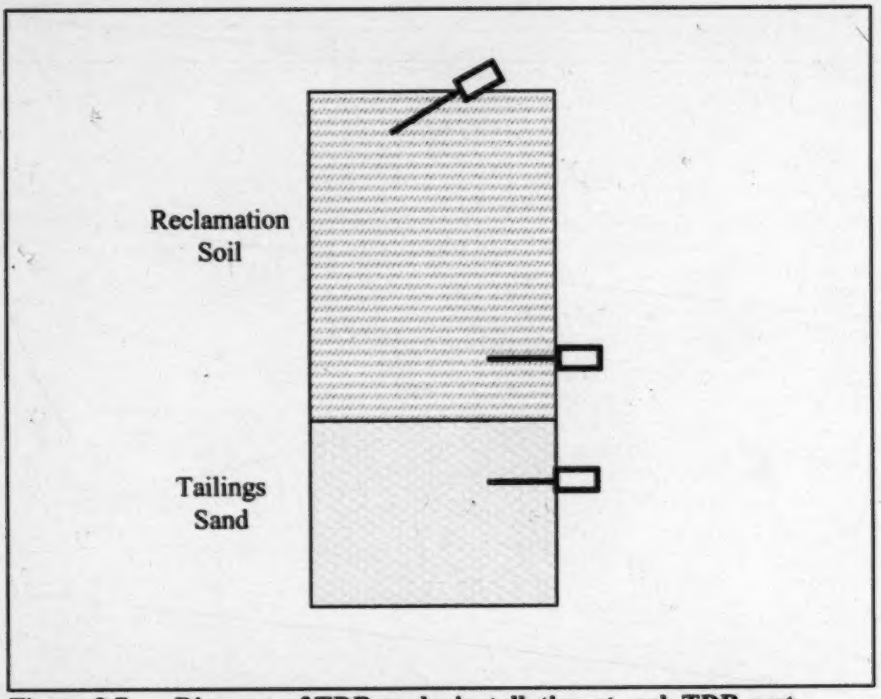

Figure 3.7 Diagram of TDR probe installation at each TDR nest

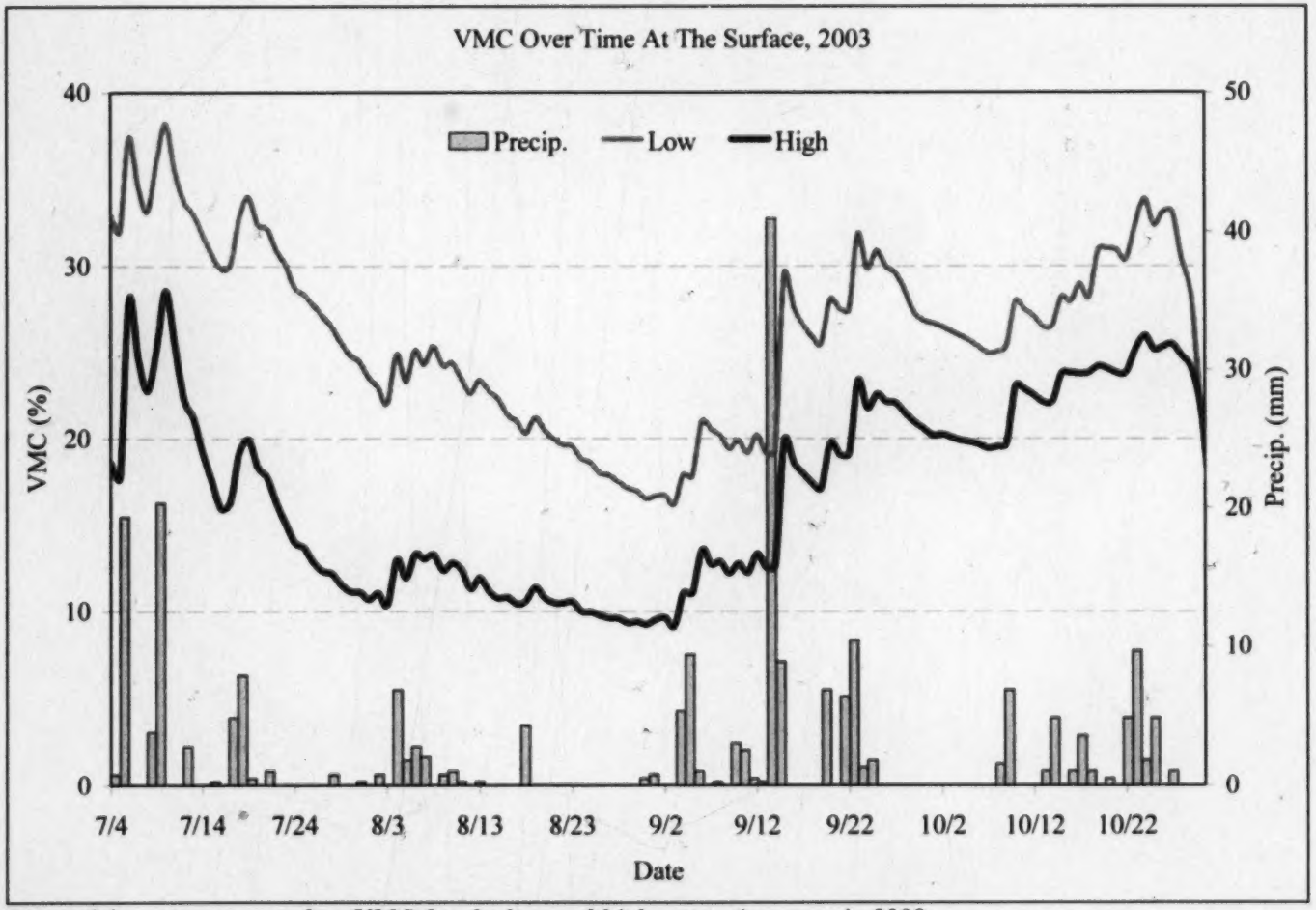

Figure 3.8 Average surface VMC for the low and high vegetation nests in 2003

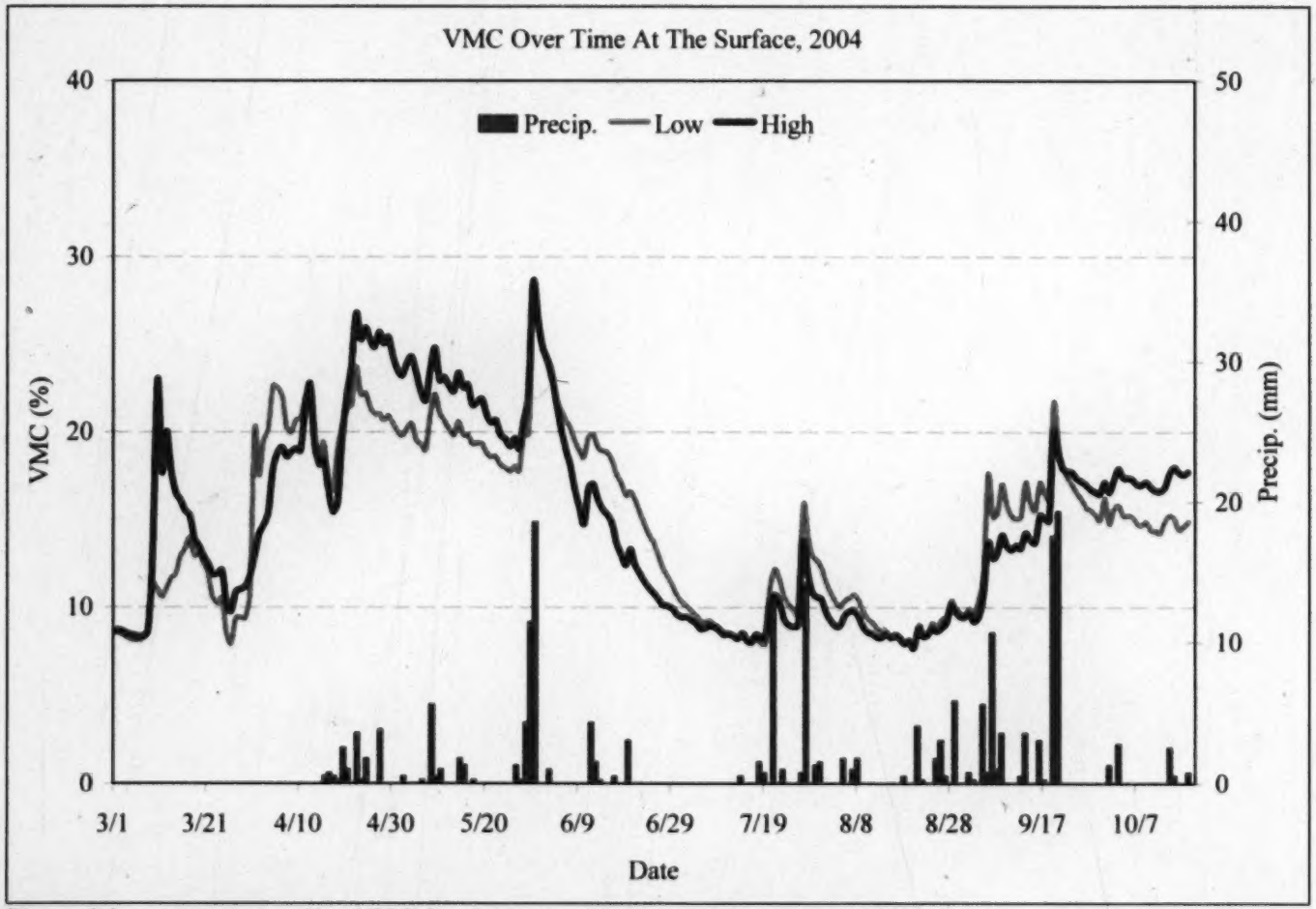

Figure 3.9 Average surface VMC for the low and high vegetation nests in 2004

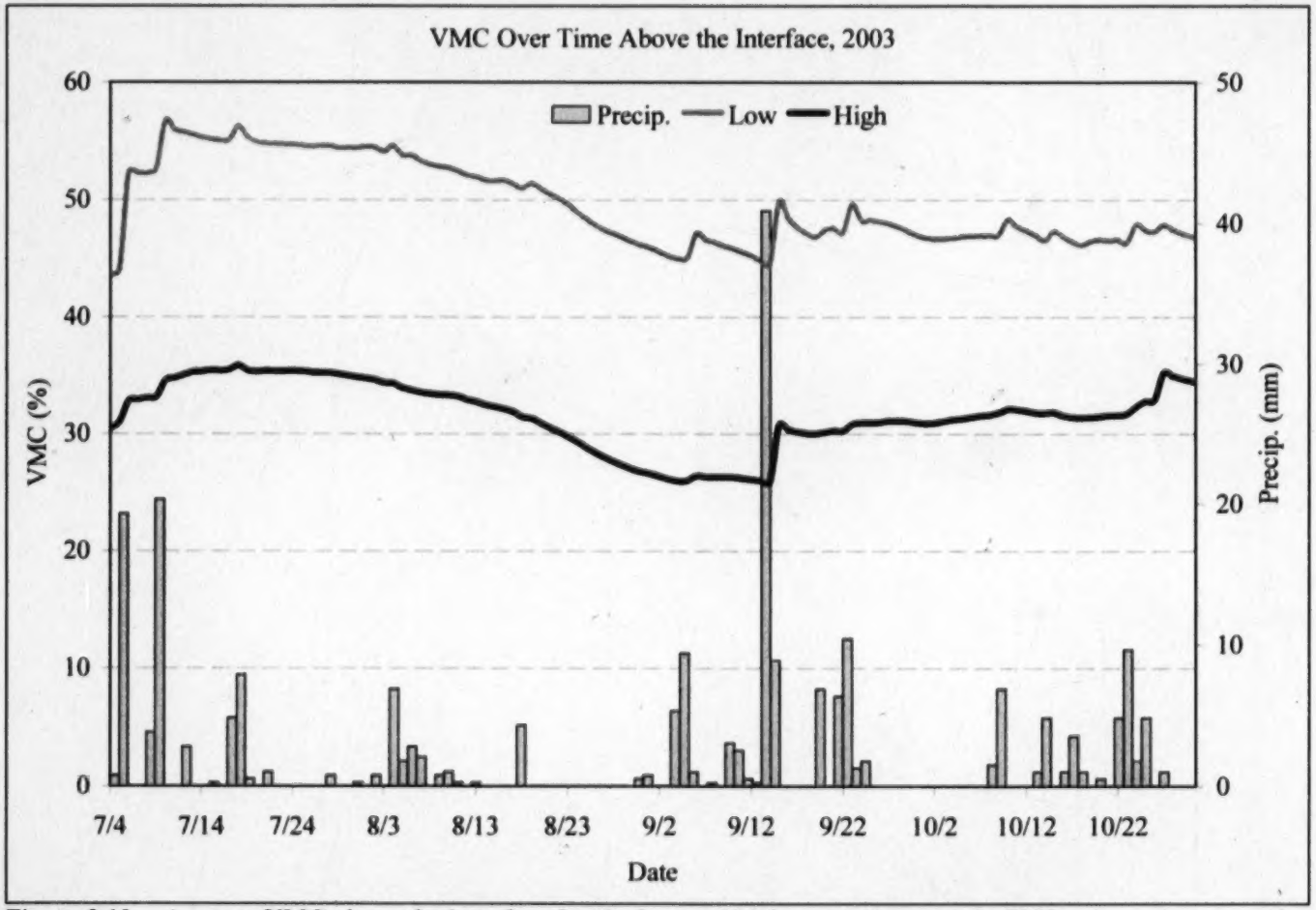

Figure 3.10 Average VMC above the interface for the low and high vegetation nests in 2003

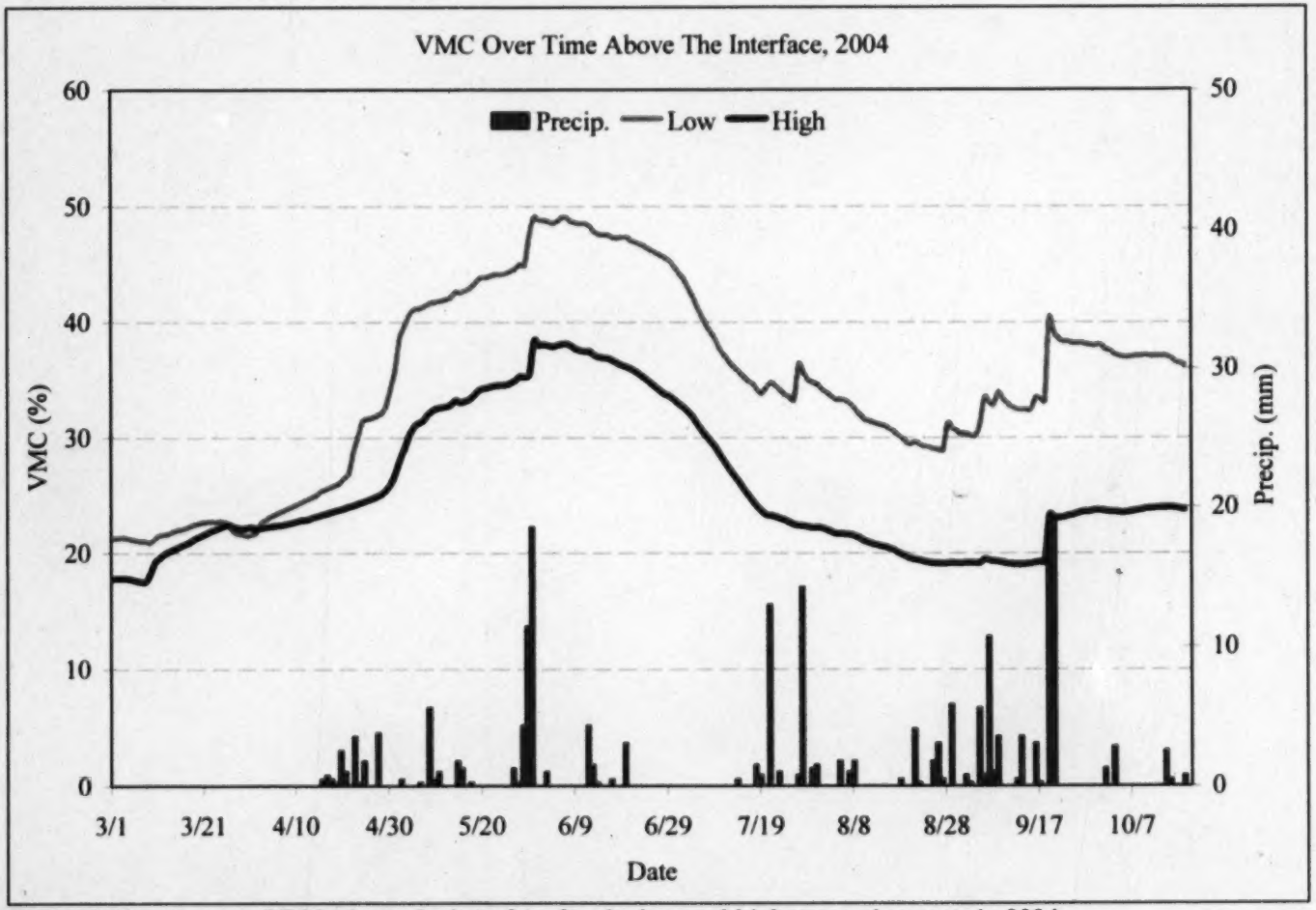

Figure 3.11 Average VMC above the interface for the low and high vegetation nests in 2004

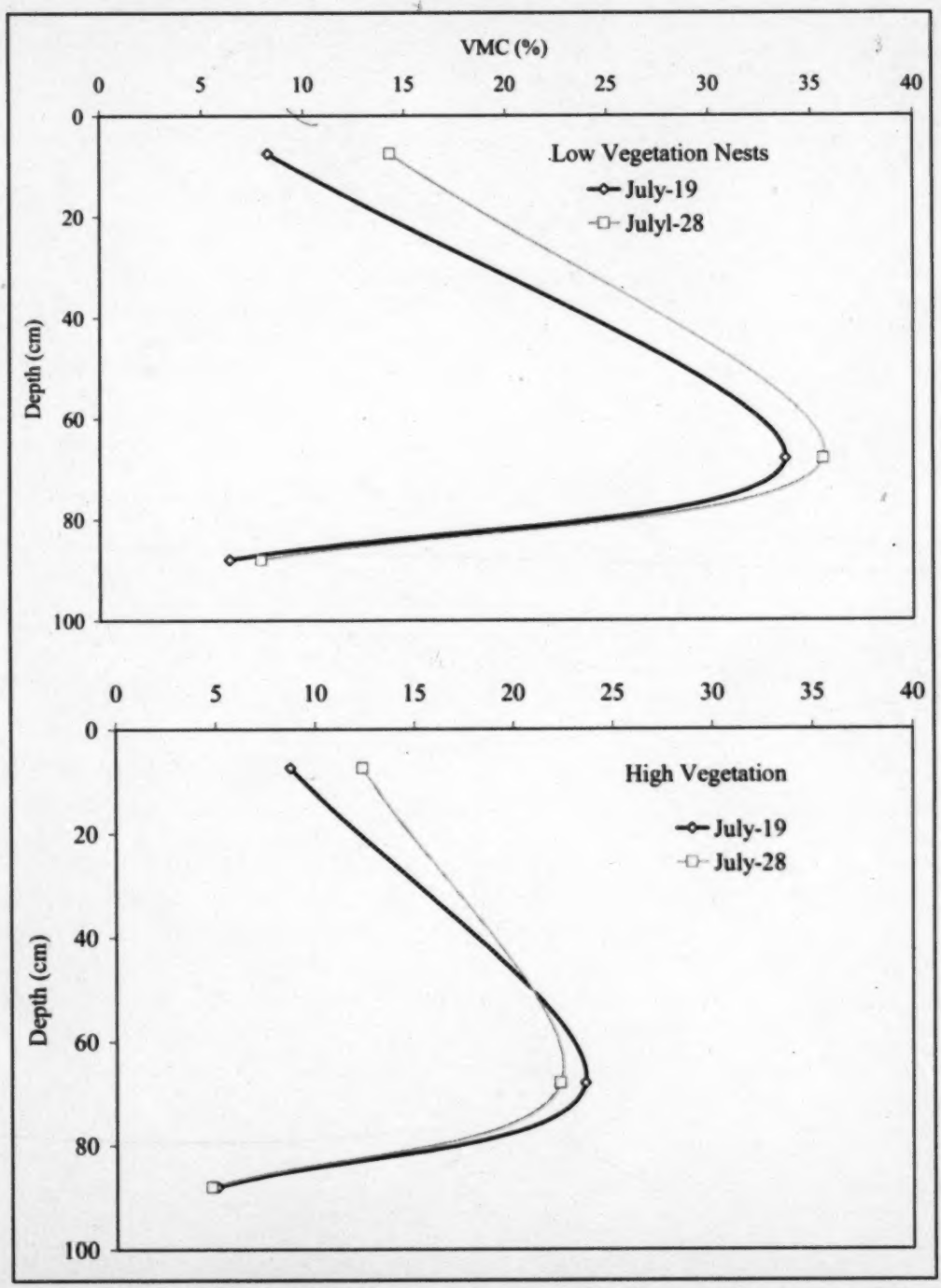

Figure 3.12 **Average VMC at depth for the low and high vegetation nests on July 19 and 28, 2004**

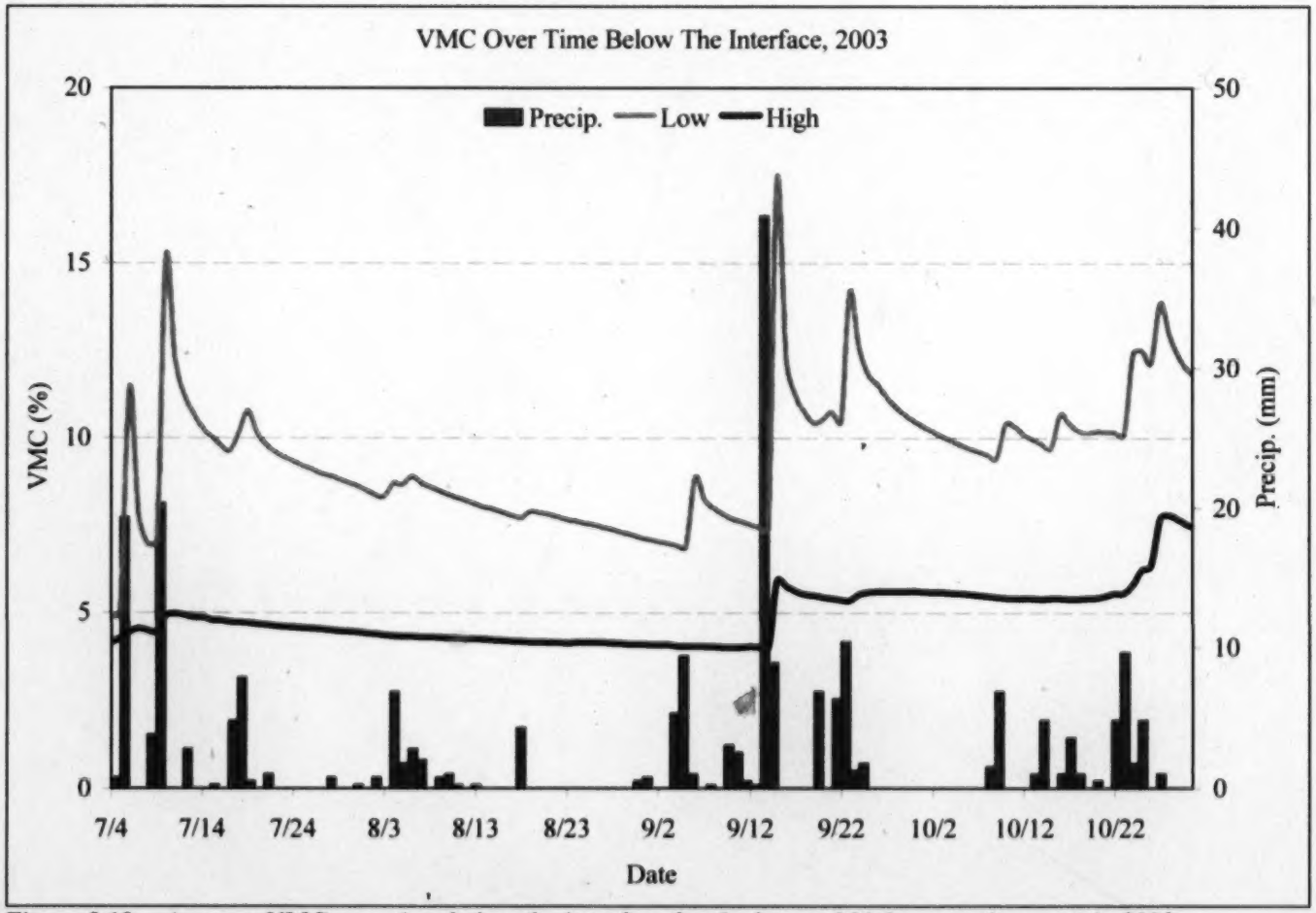

Figure 3.13 Average VMC over time below the interface for the low and high vegetation nests in 2003

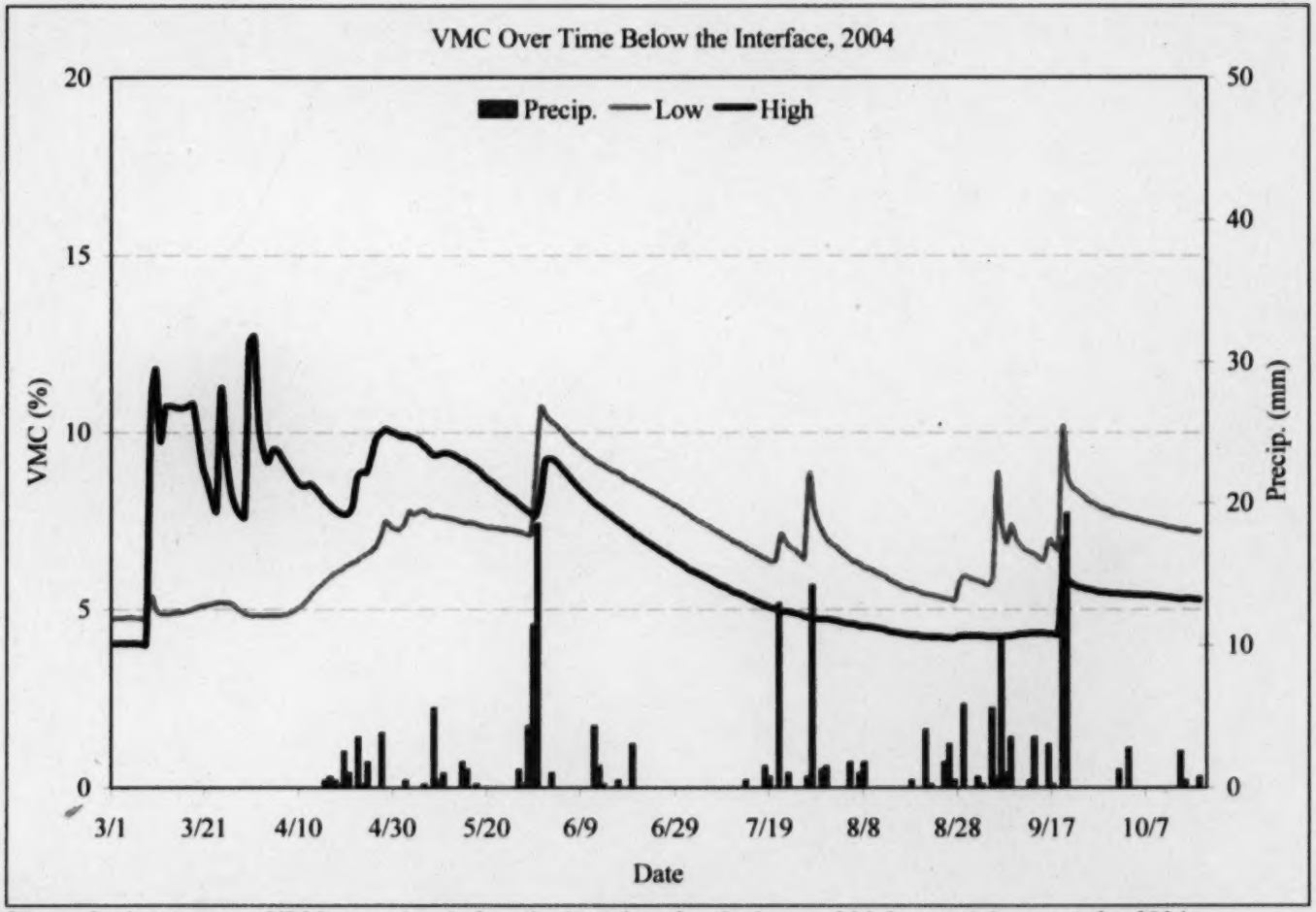

Figure 3.14 Average VMC over time below the interface for the low and high vegetation nests for 2004

Table 3.1 Long term climate normals (1971 to 2000) for Fort McMurray (Environment Canada 2003)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Year
Mean Temperature (°C)	-18.8	-13.7	-6.5	3.4	10.4	14.7	16.8	15.3	9.4	2.8	-8.5	-16.5	0.7
Mean Maximum Temperature (°C)	-13.6	-7.6	0.3	10.0	17.4	21.4	23.2	21.9	15.4	7.8	-4.2	-11.6	6.7
Mean Minimum Temperature (°C)	-24.0	-19.8	-13.2	-3.3	3.3	7.9	10.2	8.6	3.3	-2.2	-12.8	-21.4	-5.3
Mean Rainfall (mm)	0.5	0.8	1.6	9.3	34.2	74.8	81.3	72.6	45.0	18.8	2.4	1.1	342.2
Mean Snowfall (cm)	27.0	20.6	20.4	14.5	2.9	0.0	0.0	0.0	2.4	13.1	29.0	25.9	155.8
Total Precipitation (mm)	19.3	15.0	16.1	21.7	36.9	74.8	81.3	72.7	46.8	29.6	22.2	19.3	455.5

Table 3.2 Meteorological data for the Fort McMurray airport in 2003 and 2004 (Environment Canada 2004)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Year
2003													
Mean Temperature (°C)	-16.6	-18.6	-10.6	3.9	9.3	14.0	17.6	16.1	9.5	4.4	-9.4	-12.1	0.6
Mean Maximum Temperature (°C)	11.4	-12.0	-3.4	10.7	16.6	20.8	24.6	23.3	15.0	9.9	-4.0	-6.8	8.8
Mean Minimum Temperature (°C)	-21.8	-25.1	-17.8	-2.9	1.9	7.1	10.5	8.9	4.0	-1.0	-14.8	-17.3	-5.7
Mean Rainfall (mm)	0.2	0.0	1.9	8.4	39.9	84.5	69.9	48.7	86.2	35.4	0.0	0.0	375.1
Mean Snowfall (cm)	7.1	31.7	27.1	1.4	20.1	0.0	0.0	0.0	3.2	18.1	17.4	18.0	144.1
Total Precipitation (mm)	7.3	21.8	25.0	9.8	52.4	84.5	69.9	48.7	89.4	56.5	12.9	18.0	496.2
2004													
Mean Temperature (°C)	-21.4	-10.6	-6.5	3.0	5.7	13.3	18.0	12.7					1.8
Mean Maximum Temperature (°C)	-17.2	-3.6	1.3	9.8	12.2	21.4	25.8	20.1					8.7
Mean Minimum Temperature (°C)	-25.4	-17.5	-14.2	-3.9	-0.9	5.1	10.1	5.2					-5.2
Mean Rainfall (mm)	0.0	3.7	0.9	8.5	49.6	16.0	36.5	17.0					132.2
Mean Snowfall (cm)	48.7	20.4	20.3	14.5	5.0	0.0	0.0	0.0					108.9
Total Precipitation (mm)	38.3	16.9	15.0	23.0	54.6	16.0	36.5	17.0					217.3

Table 3.3 Meteorological data for Cell 32 in 2003 and 2004

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Year
2003													
Mean Temperature (°C)	-15.9	-17.4	-10.1	3.9	10.1	14.4	17.9	16.5	9.7	5.3	-8.1	-10.5	1.3
Mean Maximum Temperature (°C)	-11.5	-12.0	-4.2	9.9	15.9	20.2	24.1	23.0	14.8	10.7	-3.8	-6.6	6.7
Mean Minimum Temperature (°C)	-20.7	-22.9	-15.9	-1.5	4.0	8.7	11.9	10.5	5.1	1.2	-12.2	-14.5	-3.8
Total Precipitation (mm)	0.0	0.0	26.9	13.2	34.8	62.7	70.9	21.3	99.6	42.4	0.0	0.0	371.8
2004													
Mean Temperature (°C)	-21.2	-10.2	-5.1	3.2	6.1	14.3	18.9	13.4	8.2	1.4			2.9
Mean Maximum Temperature (°C)	-17.8	-4.1	1.0	9.4	12.4	20.6	25.6	19.6	13.2	5.9			8.6
Mean Minimum Temperature (°C)	-25.0	-15.5	-11.6	-2.5	0.6	7.6	12.1	7.6	3.5	-2.6			-2.6
Total Precipitation (mm)	0.0	0.0	0.0	15.0	47.0	10.7	34.5	21.3	67.3	8.4			204.2

Table 3.4 Vegetation properties for the low and high vegetation nests in 2003

	Vegetation Nests		
	Low	High	P Value
Total Canopy Cover (%)	15 (5 to 25) [b]	68 (50 to 100) [a]	0.021
Bare Ground (%)	66 (5 to 91) [a]	4 (0 to 10) [a]	0.058
Litter (%)	3 (2 to 4) [a]	67 (3 to 92) [a]	0.058
Live (%)	1 (1 to 2) [b]	4 (2 to 5) [a]	0.032
Moss (%)	26 (0 to 89) [a]	26 (0 to 90) [a]	0.767
Rock (%)	4 (0 to 10) [a]	0 (0 to 0) [a]	0.131
Health	1 (1 to 1) [a]	1 (1 to 2) [a]	0.317

Values reported as Mean (minimum and maximum) n = 8
Common letters in rows are not significantly different at ($p \leq 0.05$)

Table 3.5 Soil properties for the low and high vegetation nests at the surface in 2004

	Low	High	P Value
Soil Depth (cm)	78 (52 to 98) [a]	83 (60 to 106) [a]	0.564
pH	7.5 (6.9 to 7.9) [a]	7.4 (6.6 to 7.6) [a]	0.312
Electrical conductivity (dS/m)	0.8 (0.4 to 1.3) [a]	0.6 (0.4 to 1.1) [a]	0.308
Sodium adsorption ratio	1.2 (0.5 to 1.8) [a]	0.7 (0.4 to 1.0) [b]	0.017
Saturation (%)	53 (43 to 76) [a]	54 (49 to 71) [a]	0.491
Na^+ (mg/L)	46 (18 to 68) [a]	26 (17 to 39) [b]	0.027
Mg^{2+} (mg/L)	15 (2.3 to 38) [a]	22 (13 to 42) [a]	0.400
Ca^{2+} (mg/L)	112 (40 to 202) [a]	96 (56 to 166) [a]	0.723
K^+ (mg/L)	6 (3 to 9) [a]	9 (3 to 23) [a]	0.310
Cl^- (mg/L)	29 (11 to 55) [a]	40 (18 to 88) [a]	0.529
SO_4^{2-} (mg/L)	214 (54 to 422) [a]	111 (41 to 215) [a]	0.141
Organic carbon (%)	2.1 (1.3 to 3.1) [a]	3.1 (2.3 to 5.1) [a]	0.058
Organic matter (%)	3.6 (2.3 to 5.4) [a]	5.4 (4.0 to 8.7) [a]	0.066
Cu^{2+} (mg/kg)	0.91 (0.7 to 1.1) [a]	0.98 (0.80 to 1.30) [a]	0.626
Fe^{2+} (mg/kg)	38 (14 to 98) [a]	43 (22 to 57) [a]	0.248
Mn^{2+} (mg/kg)	2.7 (1.5 to 5.1) [a]	3.53 (2.30 to 6.40) [a]	0.205
Zn^{2+} (mg/kg)	0.5 (0.3 to 0.7) [a]	0.6 (0.5 to 0.9) [a]	0.246
$NO_3^- + NO_2^-$ (mg/L)	0.7 (0.7 to 0.8) [a]	0.7 (0.7 to 0.8) [a]	0.535
Available NO_3^- (mg/kg)	1.6 (1.4 to 1.8) [a]	1.7 (0.8 to 3.6) [a]	0.788
PO_4^{3-} (mg/L)	BDL (BDL to BDL)	BDL (BDL to BDL)	~
Available PO_4^{3-} (mg/kg)	1 (1 to 1) [a]	3 (1 to 9) [a]	0.913

Values reported as Mean (minimum and maximum) n = 8

Common letters in rows are not significantly different at ($p \leq 0.05$)

BDL = Below Detectable Limit for PO_4^{3-} < 1 mg/L

Table 3.6 Soil properties for the low and high vegetation nests above the interface in 2004

	Low	High	P Value
pH	7.7 (7.3 to 7.9) [a]	7.2 (7.0 to 7.5) [a]	0.058
Electrical conductivity (dS/m)	0.7 (0.2 to 1.0) [a]	2.4 (0.8 to 3.2) [a]	0.110
Sodium adsorption ratio	2.0 (0.9 to 2.9) [a]	1.2 (1.0 to 1.6) [a]	0.381
Saturation (%)	49 (47 to 50) [a]	63 (42 to 105) [a]	0.243
Na^+ (mg/L)	67 (19 to 106) [a]	109 (44 to 158) [a]	0.248
Mg^{2+} (mg/L)	14 (6 to 22) [b]	105 (24 to 189) [a]	0.021
Ca^{2+} (mg/L)	64 (24 to 102) [b]	513 (117 to 768) [a]	0.021
K^+ (mg/L)	3 (3 to 3) [a]	7 (4 to 10) [b]	0.014
Cl^- (mg/L)	10 (7 to 13) [a]	31 (12 to 51) [a]	0.059
SO_4^{2-} (mg/L)	260 (29 to 400) [a]	1480 (138 to 2200) [a]	0.149
$NO_3^- + NO_2^-$ (mg/L)	0.8 (0.7 to 0.8) [a]	5.4 (0.7 to 12.7) [a]	0.536
Available NO_3^- (mg/kg)	1.6 (0.8 to 2) [a]	3 (0.4 to 5.2) [a]	0.773
PO_4^{3-} (mg/L)	BDL (BDL to BDL)	BDL (BDL to BDL)	~
Available PO_4^{3-} (mg/kg)	0 (BDL to 1) [a]	1 (BDL to 3) [a]	1.000

Values reported as Mean (minimum and maximum) n = 4

Common letters in rows are not significantly different at ($p \leq 0.05$)

BDL = Below Detectable Limit for PO_4^{3-} and Available PO_4^{3-} < 1 mg/L

Table 3.7 Soil properties for the low and high vegetation nests below the interface in 2004

	Low	High	P Value
pH	7.9 (7.5 to 8.1) [a]	7.6 (7.4 to 7.8) [a]	0.144
Electrical conductivity (dS/m)	0.4 (0.2 to 0.5) [b]	1.0 (0.5 to 1.6) [a]	0.046
Sodium adsorption ratio	1.7 (1.2 to 2.7) [a]	1.0 (0.8 to 1.2) [b]	0.038
Saturation (%)	25 (21 to 27) [a]	27 (26 to 28) [a]	0.544
Na^+ (mg/L)	41 (20 to 60) [a]	48 (29 to 81) [a]	0.773
Mg^{2+} (mg/L)	10 (7 to 12) [b]	32 (12 to 51) [a]	0.029
Ca^{2+} (mg/L)	31 (12 to 52) [b]	141 (54 to 262) [a]	0.021
K^+ (mg/L)	3 (2 to 5) [a]	5 (4 to 6) [a]	0.076
Cl^- (mg/L)	9 (6 to 11) [a]	13 (9 to 21) [a]	0.110
SO_4^{2-} (mg/L)	117 (18 to 172) [a]	442 (116 to 921) [a]	0.149
$NO_3^- + NO_2^-$ (mg/L)	0.9 (0.8 to 1.0) [a]	3.0 (0.7 to 5.4) [a]	1.000
Available NO_3^- (mg/kg)	1.2 (1 to 1.6) [a]	1.3 (0 to 2) [a]	0.456
PO_4^{3-} (mg/L)	BDL (BDL to BDL)	BDL (BDL to BDL)	~
Available PO_4^{3-} (mg/kg)	0 (BDL to 1) [a]	1 (BDL to 2) [a]	0.155

Values reported as Mean (minimum and maximum) n = 4

Common letters in rows are not significantly different at ($p \leq 0.05$)

BDL = Below Detectable Limit for PO_4^{3-} and Available PO_4^{3-} < 1 mg/L

CHAPTER IV. SYNTHESIS

1.0 VEGETATION AND SOIL CHEMICAL AND PHYSICAL INTERACTIONS ON A TAILINGS SAND STORAGE FACILITY

1.1 Cell 32

The plant community was comprised of early successional, ruderal species and is very different from the desired end land use of productive forestry. The domination of weedy species was expected as this is typical of recently disturbed ecosystems. Although salinity, as measured by electrical conductivity, did not appear to negatively affect the plant community, the high concentrations of ions (sodium, chloride and sulphate) in combination were affecting overall reclamation success. In addition the higher concentration of sodium in relation to calcium and magnesium in the low vegetation treatments was influencing soil properties that had secondary effects on the vegetation. Nutrient deficiencies, particularly potassium, were also negatively impacting the vegetation.

1.2 Cell 46

The plant community on Cell 46 is also dominated by early successional ruderal species typical of recently disturbed ecosystems. The highest relative canopy cover was from bluejoint (*Calamagrostis canadensis* (Michx.) Beauv.) which could have implications for the future establishment of tree species. Electrical conductivities were not statistically different among treatments but the average electrical conductivities were high enough to theoretically affect vegetation (> 2dS/m). However, plant parameters measured did not show a vegetation response to these high values. This may be due to the interactions of higher organic matter buffering against the higher electrical conductivities. In addition the majority of vegetation species established on Cell 46 had a degree of salt tolerance. Electrical conductivities in the reclamation soil may increase over time through the movement of tailings water into the reclamation soil and increases in electrical conductivities of tailings water with time.

For Cell 46 the medium vegetation treatment unexpectedly had significantly higher SAR than the low vegetation treatment. If the SAR increases within the medium

vegetation areas, this could result in changes to soil properties, which could produce negative secondary effects for vegetation, especially if they increase beyond the tolerance limits of the established vegetation. Although this negative effect could be buffered by the higher soil organic matter content on the cell. It appears that deficient soil nutrients were impacting the low vegetation areas coupled with the interactions of soil pH and organic matter. The low reclamation soil depths were also affecting the plant community, as the depth of reclamation soil is not sufficient to provide a suitable growth medium over the tailings.

2.0 Vegetation and Soil Moisture Interactions on a Tailings Sand Storage Facility

Volumetric moisture contents (VMC) were higher in the low vegetation nests at the surface, above and below the reclamation soil / tailings sand interface but excess soil moisture or saturated conditions were not impacting vegetation on Cell 32. Vegetation would experience periods of water stress (VMC below the wilting point) but these periods were of short duration and also typical of boreal forest ecosystems. The differences in VMC between low and high vegetation nests may be attributed to differences in evapotranspiration, canopy interception and percolation between vegetation nests.

At the interface of the reclamation soil and tailings sand, water movement is restricted. Possible hydrophobicity of the tailings material and/or the inherent differences in physical properties of the reclamation soil and tailings sand explain this. The implications for vegetation were increased water availability in the reclamation soil and a build up of ions above the interface.

3.0 Recommendations for Management

Cell 32 has developed a plant community typical of a disturbed ecosystem but there are some soil chemical properties that were affecting plant community establishment and development. An average reclamation soil depth of 80 cm was sufficient to provide an adequate growth medium for vegetation. Future reclamation practices should attempt to limit the fluctuations in this depth as it was noted that the

reclamation soil depth was only 45 cm for some plots. Although not statistically significant, the low vegetation plots did have, on average, lower reclamation soil depths.

Although not included in the original study design, it became apparent, through statistical investigations, that the toe slope had different soil properties than the other slopes. For the 0 to 10 cm interval it had lower copper, calcium, magnesium and potassium and higher iron, chloride and SAR. At the 10 to 20 cm depth interval it had lower copper, calcium and potassium and higher chloride, sodium and SAR. Given the location of the toe slope at the base of the structure, hypothetically receiving a greater proportion of tailings seepage water which may be increasing concentrations of chemical parameters observed. Given these differences the toe slope may prove to be a greater challenge than the other slopes to achieving reclamation success.

At the interface of the reclamation soil and tailings sand, water movement is restricted. The inherent differences in physical properties of the reclamation soil and tailings sand and/or possible hydrophobicity of the tailings material may explain this. This lead to increases in available water for plant use and increased concentration of soluble ions above the interface due to leaching through the topsoil and concentrating above the interface. If the increases in concentrations are above the acceptable tolerance limits of the vegetation and the roots of the vegetation access water from this area complications for vegetation growth may occur.

For Cell 46 continued use of the reclamation soil prescription of a peat/mineral mix over secondary material to a total depth of 35 cm is questionable, as the vegetation was clearly impacted by low soil depths. Attempts should be made to incorporate the peat material with the secondary material so that an improved growth medium is provided for vegetation or during topsoil harvest, a larger proportion of mineral soil should be incorporated in the mix. The majority of the desired species for the SWSS are upland species not adapted to organic soils. The incorporation of a greater proportion of mineral soil into the peat mix would allow for a more desirable growth medium for these upland species. Although the higher organic matter content of the soil may serve as a buffer against the higher sodicities and electrical conductivies which allowed the higher vegetation cover in areas with the highest SAR and salt contents.

The use of peat over secondary material may be preferred for areas that are low-lying, such as the lateral waterways on Cell 32 and the slopes at the base of cells, to initiate the formation of wetland plant communities. This would have the added benefit of increasing diversity to the final reclaimed ecosystem and placing this reclamation material in areas that would mimic the natural conditions in which they are found.

Salinity at this time is not a limiting factor for vegetation development in either cell as there was not a statistical significant difference between vegetation treatments on both Cells 32 and 46. A greater concern is noted for Cell 46 where electrical conductivities were generally higher than on Cell 32 and may increase in the reclamation soil with time. These average electrical conductivities were >2 dS/m which is the threshold for which vegetation with low salinity tolerances may be affected.

4.0 SUGGESTIONS FOR FUTURE RESEARCH

4.1 Continuation of Vegetation Monitoring

The one time assessment of vegetation, conducted in this study, is inadequate to predict the long-term sustainability and successional trends of the plant community. The establishment of vegetation in the short-term will not necessarily accurately represent the future plant community composition, due to successional trends with time. Particular emphasis should be placed on the establishment of native vegetation, desired in the final reclaimed ecosystem for its ability to compete with the ruderal species already established. Particular emphasis should also be focused on the persistence of bluejoint on Cell 46 as it may affect the establishment of tree species.

4.2 Continuation of Soil Monitoring

The one time assessment of soils, conducted in this study, is also inadequate to predict the long-term trends in soil development. The low topsoil depths and soil configurations on Cell 46 present a particular concern and research should further evaluate the ability of 35 cm total depth and soil prescription to provide an adequate growth medium for vegetation, especially species desired in the end land use.

4.3 Investigate the Apparent Textural Discontinuity at the Reclamation Soil and Tailings Sand Interface

This study and previous studies (Chaikowsky 2003) have noted that the tailings sands may be hydrophobic and coupled with the textural discontinuity at the interface, may affect water movement on Cell 32 and Cell 46. A study should be designed to assess the overall effects that the interface has on plant community development. Consideration should be given to the ability of the interface to provide increased water availability for plants through the limitation of percolation into the tailings sand balanced by the potential for increased concentrations of cations and ions above the interface, caused by the precipitation leaching through the soil profile and pooling above the interface. Given the conflicting results of this study that found tailings water is not moving into the reclamation soil and Macyk and Faught (2001) who suggested that tailings water is impacting the reclamation soil, further investigation is needed. It is noted that slope position within each bench may have an effect on tailings water movement into the reclamation soil as it is expected that on lower slope positions greater tailings water movement into the reclamation soil may be expected. Any study design should address this issue.

5.0 LITERATURE CITED

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